LATIN AMERICA
COFFEE
CARBON FOOTPRINT
BASELINE STUDY
BRAZIL, COLOMBIA, HONDURAS, MEXICO, PERU

VERSION 1.0 - MARCH 2026

CONSERVATION INTERNATIONAL

SUSTAINABLE COFFEE CHALLENGE

meo CARBON SOLUTIONS

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ACRONYMS

AGB	Above Ground Biomass
API	Application Programming Interface
BGB	Below Ground Biomass
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
CFA	Cool Farm Alliance
CFP	Cool Farm Platform
CI	Conservation International
CIRAD	French Agricultural Research Centre for International Development
dLUC	Direct Land Use Change
DOM	Dead Organic Matter
EF	Emission Factor
GBE	Green Bean Equivalent
GHG	Greenhouse Gas
GHGP	Greenhouse Gas Protocol
GRAS	Global Risk Assessment Service
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
IQR	Interquartile Range
sLUC	Statistical Land Use Change
LCA	Life Cycle Assessment
LMU	Land Management Unit
LUC	Land Use Change
LSRS	Land Sector and Removals Standard
MCS	Meo Carbon Solutions
MoE	Margin of Error
QC	Quality Control
SBTi	Science Based Target Initiative
SCC	Sustainable Coffee Challenge
SD	Standard Deviation
SE	Standard Error
jdLUC	jurisdictional direct LUC
SOC	Soil Organic Carbon
TSP	Technical Service Provider

ABOUT THIS REPORT

This report presents the results of the Latin America Coffee Carbon Footprint Baseline Study, developed through a pre-competitive collaboration among roasters, supply chain partners, technical experts, and relevant coffee sector stakeholders. It provides nationally representative, farm-gate greenhouse gas (GHG) emission baselines for major coffee-producing countries in the region, based on harmonized primary data collection and aligned carbon accounting methodologies.

The report is designed to support coffee companies, traders, roasters, and sector actors in strengthening GHG accounting, benchmarking emission intensities, and identifying priority mitigation opportunities within their supply chains. While grounded in rigorous statistical analysis and methodological alignment, the study is practical in orientation, intended to inform decision-making, target setting, and investment strategies.

Recognizing that stakeholders are at different stages of their climate journeys, the report combines technical transparency with actionable insights. It does not prescribe a single pathway for implementation, nor does it replace company-level inventories or certification requirements. Rather, it provides a robust, sector-aligned reference point that can be used to improve data quality, foster methodological convergence, and guide future multi-year and multi-stakeholder climate action in the coffee sector.

ACKNOWLEDGEMENTS

The support of these partners reflects their contribution to the study, not necessarily an endorsement of the results

EXECUTIVE SUMMARY

CONTEXT AND RATIONALE

Coffee supply chains face increasing pressure to quantify and reduce Scope 1, 2 and 3 greenhouse gas (GHG) emissions while maintaining producer livelihoods and supply resilience under accelerating climate change. Latin America represents a strategically critical coffee-producing region, characterized by diverse production systems, management intensities, and processing practices. Robust, transparent, and comparable farm-gate carbon footprint baselines for this region are essential to driving credible corporate climate commitments, sector-wide benchmarking, and the prioritization of mitigation actions that are both environmentally effective and operationally feasible.

The Latin America Coffee Carbon Footprint Baseline Study was conducted to address this need by establishing nationally representative farm-gate GHG emission baselines for coffee production in Brazil, Colombia, Honduras, Mexico, and Peru, covering Arabica coffee in all five countries and Robusta coffee in Brazil. The study was initiated under the Sustainable Coffee Challenge, led by Conservation International, and implemented by Meo Carbon Solutions (MCS) in consortium with Global Risk Assessment Services (GRAS) and 4C Services.

The study was designed as a highly collaborative, pre-competitive initiative, with governance and technical oversight provided through close coordination between implementing partners, roasters, and traders. Participating roasters played a key role in shaping the study's scope, methodological alignment, and interpretation of results, ensuring relevance for Scope 3 accounting and corporate climate strategies. Traders and other service providers were equally instrumental, providing in-kind data collection, facilitating farm access, supporting enumerator coordination, validating contextual assumptions, and contributing operational insights throughout the survey application and quality-control phases. Regular consultations, technical exchanges, and feedback loops were embedded in the study design, making stakeholder engagement not only a supporting element but a core component of the baseline's development, credibility, and sectoral ownership.

STUDY PURPOSE AND KEY QUESTIONS

The study was designed as a baseline-setting and learning exercise, rather than a farm-level performance ranking or a full life-cycle assessment. Its primary purpose was to support corporate GHG accounting and strategic mitigation planning by providing harmonized, decision-relevant farm-gate emission intensities.

Specifically, in addition to supporting an aligned sector-wide approach to assessing and analyzing on-farm GHG emissions, the study sought to answer three core questions:

- What is the average farm-gate carbon footprint of coffee production in major Latin American origins, expressed in a form suitable for corporate GHG inventories?
- Which on-farm activities consistently drive emissions across countries, and where does farm-level heterogeneity materially affect interpretation?
- How robust and comparable are national-level baselines derived from heterogeneous primary farm data and different calculation tools?

SCOPE, DESIGN LOGIC, AND ANALYTICAL APPROACH

To establish the average farm-gate coffee carbon footprint in the target countries, a farm-gate system boundary and a functional unit of kilogram (kg) of carbon dioxide equivalent (CO_2-eq) per kg of green bean equivalent (GBE) were used. This functional unit represents the total amount of GHG emissions generated per kg of standardized green coffee output. Emissions from different GHGs, including carbon dioxide, hereafter CO_2; methane, hereafter CH_4; and nitrous oxide, hereafter N_2O; were quantified within the defined system boundary, aggregated, and converted into a common metric, the CO_2-eq, using their respective global warming potentials. The summed CO_2-eq emissions were then divided by the total amount of coffee produced. Because production volumes at the farm level may be reported in different forms (e.g., fresh cherries, wet parchment, dry parchment, or green beans), standardized conversion factors were applied to harmonize all outputs into green GBE. After conversion to GBE, total farm-level emissions were divided by the corresponding quantity of GBE produced, yielding the emission intensity.

Activities beyond the farm gate, including centralized processing, export, roasting, and retail, were intentionally excluded to focus analytical attention on on-farm emission sources, where critical mitigation levers are highly actionable in collaboration with supply chain actors.

Primary data were collected through large-scale farm surveys, implemented by trained enumerators across participating supply chains. A stratified, production-weighted sampling framework was applied to ensure national representativeness, informed by expert input from the third-party reviewer, CIRAD, and explicit consideration of production system heterogeneity.

Carbon footprint calculations were conducted primarily using the Cool Farm Platform perennials module version 2.0 (hereafter, CFP), selected for its widespread use and standardized structure. To strengthen confidence in results, a comparative analysis

using the 4C Carbon Footprint Add-On (hereafter, 4C) was conducted, enabling cross-validation of emission patterns and magnitude. An additional comparative analysis using Simapro is forthcoming, provided in-kind by Lavazza.

RESULTS

The results demonstrate that national-level farm-gate carbon footprint baselines vary across the five Latin American origins assessed. Average emission intensities are estimated at:

BRAZIL

3.22 kg
CO_2-eq per
kg GBE for (Arabica)

2.51 kg
CO_2-eq per
kg GBE (Robusta)

COLOMBIA

5.59 KG
CO_2-eq per kg
GBE

HONDURAS

4.87 KG
CO_2-eq per kg
GBE

MEXICO

1.46 KG
CO_2-eq per kg
GBE

PERU

2.84 KG
CO_2-eq per kg
GBE

Figure 1: Baseline results from CFP per country

These differences reflect structural variation in production systems, including fertilizer input intensity, crop residue management practices, and the prevalence and type of wet processing, rather than differences in data quality or methodological application. While farm-level variability within each country is substantial, the national-level results provide robust, comparable baselines suitable for benchmarking, and farm-level decision making[1].

SOURCE	BRAZIL ARABICA	BRAZIL ROBUSTA	COLOMBIA	HONDURAS	MEXICO	PERU
Fertilizer use (production and application)	1.9	1.53	3.35	2.33	0.69	0.51

[1] Interpretation of these results should consider the methodological boundaries and data constraints discussed in subsequent sections. Key limitations include assumptions embedded in emission factors and modeling tools, particularly those related to residue generation and estimation, the application of allometric equations, default nitrogen content values, and COD/BOD parameters, as well as uncertainties inherent in self-reported farm data. These factors may influence absolute emission magnitudes; however, the harmonized methodological framework applied across all origins supports reasonable cross-country comparability within the context of this baseline study.

Crop residues	1.09	0.69	1.82	2.00	0.58	1.89
Machinery operations	0.09	0.08	0.30	0.25	0.12	0.28
Transport	0.07	0.05	0.01	0.02	0.02	0.04
Fuel & energy	0.03	0.05	0.07	0.03	0.02	0.02
Wastewater	0.02	0.001	0.04	0.21	0.02	0.11
Irrigation	0.002	0.10	0	0	0	0
Pesticides	0.001	0.004	0.001	0.008	0.0003	0.0008
Non-crop biomass estimates	-1.47	-0.14	-0.34	-0.187	-0.07	-0.184
Baseline Results (excluding non-crop biomass estimates)	**3.22**	**2.51**	**5.59**	**4.87**	**1.46**	**2.84**

Table 1: Summary of emissions per country and source

INTERPRETATION, ASSUMPTIONS, AND LIMITATIONS

The farm-level baselines in this report are calculated for a single reporting year, consistent with the Greenhouse Gas Protocol (GHGP) Corporate Accounting and Reporting Standard. While this approach does not capture inter-annual variability in yields or management intensity, it ensures direct usability for annual reporting, benchmarking, and target tracking. At the same time, multi-annual data were collected for selected parameters, such as yields (see Table 9) and fertilizer applications, allowing comparison between the assessment year and preceding production periods and supporting internal validation of reported values. Whether multi-year averaging approaches should be systematically applied in perennial systems is ultimately a methodological choice that should be determined by industry actors based on the intended purpose of the assessment (e.g., corporate reporting, life cycle assessment, product footprint assessment, etc.). Clear alignment on how to best incorporate multi-year data, and for what purposes, would be needed to enhance consistency and comparability across future sector initiatives.

Certain processes, most notably soil organic carbon changes and land-use change emissions, were excluded from the core reported baselines due to considerations related to methodological readiness. In this context, methodological readiness refers specifically to the fact that, during the study implementation period, the CFP was undergoing revisions to its methodology for estimating soil organic carbon changes and land-use change emissions. The updated calculation framework was not yet operational or consistently available for application across all assessments at the time the analyses were conducted. To avoid inconsistencies arising from partial application

of evolving methodologies, these processes were excluded from the core baseline results. However, land-use change dynamics were assessed separately using the 4C, though they are not integrated into the main baseline values.

Further modeling-based limitations, such as those related to the CFP approach to residue management and wastewater treatment, are described throughout the body of the report. Meanwhile, as with all farm-level carbon accounting, results rely on self-reported activity data and standardized emission factors, introducing unavoidable uncertainty at the individual farm level. In addition, surveyed farms vary in practices and degrees of processing infrastructure, leaving a gap in analysis related to off-farm processing.

Importantly, the study is not intended to rank farms or evaluate individual producer performance. Rather, it provides structural, national farm-gate baselines suitable for strategic analysis and learning. Observed differences in farm-gate distributions reflect real heterogeneity and do not undermine the representativeness or decision-relevance of national averages.

It should also be noted that at the time of publication of these results, the GHGP's Land Sector and Removals Standard (LSRS) had only recently been released. The present study was designed and implemented prior to the finalization of this new standard and therefore does not fully align with its updated requirements and accounting structure for land-related emissions and removals. Future assessments in the coffee sector should consider the implications of the updated LSRS and evaluate how its guidance may be integrated into methodological design, particularly with respect to soil carbon dynamics, land-use change accounting, and removals reporting.

IMPLICATIONS AND PATH FORWARD

The study demonstrates that credible and comparable farm-gate baselines can be established on a national scale despite high heterogeneity in coffee production systems.

These national baseline values are intended to serve as sector-level reference points for benchmarking, strategic planning, hotspot identification, and pre-competitive dialogue among supply chain actors. They are suitable for informing corporate Scope 3 accounting, particularly as baseline values under Category 1 (Purchased Goods and Services) as well as for sectoral target-setting discussions. However, they are not intended to replace farm-specific assessments, nor should they be used as direct performance benchmarks for individual producers or carbon claims.

Looking forward, as methodologies mature, future studies would benefit from improved approaches to multi-year data collection and integration, enhanced characterization of residue biomass and processing systems, and the integration of

soil carbon and land-use-change modules. In addition to their contributions to learning, the results underscore the value of pre-competitive collaboration, shared benchmarks, and harmonized data collection approaches that reduce reporting burdens while strengthening the evidence base for climate action in coffee supply chains. Continued sector-wide collaboration will be essential to ensure methodological alignment and consistent application across future initiatives.

1. INTRODUCTION

The global coffee sector faces increasing pressure to address climate change by reducing GHG emissions across its supply chains. Coffee production, particularly in Latin America, plays a critical role in this conversation due to agriculture's significant contributions to GHG emissions at scale. To assess the details of this contribution and explore opportunities for GHG emissions reduction, the Sustainable Coffee Challenge, led by Conservation International (CI), launched the Latin America Coffee Carbon Footprint Baseline Study in 2024, a landmark study to establish national carbon footprint baselines for Arabica coffee production in five key origins: Brazil, Colombia, Honduras, Mexico, and Peru; and Robusta coffee production in one origin: Brazil.

Supported and governed by nine leading coffee roasters, known as the Consortium Partners—Costa Coffee, JDE Peet's, Keurig Dr Pepper, Lavazza, Melitta, Mother Parkers, Nestle, Starbucks, and Tchibo—the study sought to provide the industry with robust and open-access national carbon footprint baselines, and related analysis, for coffee production in five key origins. It also aimed to develop and apply an aligned sector-wide approach to assessing and analyzing on-farm GHG emissions, including unique methods of sampling and data collection. In doing so, it built on a similar study led by USAID Green Invest Asia (hereafter, USAID GIA) that, with wide industry support and engagement, established national-level carbon footprint baselines for Robusta coffee production in Indonesia and Vietnam in 2023.

To launch the Latin America Coffee Carbon Footprint Baseline Study, the Sustainable Coffee Challenge hired Meo Carbon Solutions (MCS) to serve as the Technical Service Provider (TSP), in consortium with Global Risk Assessment Services (GRAS) and 4C Services. MCS has extensive expertise in carbon accounting and sustainable supply chain development in the coffee sector and beyond. Finally, to ensure methodological rigor, scientific credibility, and independent technical oversight, CIRAD (Centre de coopération internationale en recherche agronomique pour le développement) served as a third-party reviewer of the study design, analytical approach, and key findings.

2. STUDY DESCRIPTION

2.1. STUDY DESIGN

To begin, MCS developed a farm survey aligned with the Cool Farm Platform perennials module version 2.0 (hereafter, CFP), and a representative sampling framework aligned with the GHG Protocol (GHGP) and Latin American context.

To distribute survey application across the five origins, the study relied on the pre-competitive collaboration of 13 Supplier Partners—Caravela, Cofco International, Cooxupé, ECOM, Hacofco, LDC, NKG, OFI, RGC, San Fransico Bay Coffee, Sucafina, Sucden, and Volcafe—as well as one civil-society organization, HRNS, who each contributed in-kind by deploying their technical in-country field teams to collect required data. The enumerators attended virtual training on farm survey application, selected participating farmers based on a randomization protocol, and collaborated with MCS to ensure quality data entries. Remaining gaps in the sample were filled through contracted data collection with five field-level organizations—Agrobiota, Fundecafé, CoHonducafe, HVC Exportaciones, Kua'nu Raíces Agrícolas—and one consultant in Peru, James Astuhuaman, who followed the same trainings and farmer selection process. Touton and The Coffee Source both contributed financially to support contracted data collection.

Once all field-level data was collected, MCS conducted a thorough cleaning process and ran the fully cleaned datasets through the CFP, which was chosen by Consortium Partners as the main analysis tool for the study. MCS additionally ran the data through 4C's Carbon Footprint Add-On (hereafter, the 4C tool) to conduct a comparative analysis and ensure greater confidence in the results. An additional comparative analysis using Simapro, conducted in-kind by Lavazza, is forthcoming.

The present report documents the details of available data analysis, and the resulting national farm-gate carbon footprint baselines. It also encourages further pre-competitive collaboration to accelerate climate action, highlights important opportunities for emissions reduction, and encourages study replication as well as areas for improvement. Specifically, it identifies the relevance of parallel work streams to further assess farm archetypes, improved approaches to crop residue management and wastewater management, and more.

2.2. PURPOSE AND OBJECTIVES OF THE STUDY

The Latin America Coffee Carbon Footprint Baseline Study was designed with the primary objective of establishing robust, nationally representative farm-gate GHG emission baselines for coffee production in five key Latin American origins.

BRAZIL   COLOMBIA   HONDURAS   MEXICO   PERU

Figure 2: Countries in scope

Beyond this core objective, the study was also explicitly conceived as a learning-oriented, pre-competitive initiative to advance methodological alignment, improve sector-wide understanding of emission drivers, and support evidence-based climate action across the coffee industry.

In addition to quantifying national emission intensities, the study aimed to:

- Identify key sources and drivers of on-farm GHG emissions, including fertilizer use, crop residue management, wastewater management, energy use, and transport;
- Assess the relative contribution of different management practices to overall emission outcomes across countries;
- Explore opportunities for emission reduction by highlighting structural hotspots and variability within national production systems;
- Provide a transparent and standardized dataset that can support future methodological refinement, benchmarking exercises, and scenario analysis;
- Contribute to industry learning and alignment by applying a shared accounting framework and openly documenting assumptions, limitations, and uncertainties.

In addition, the study was designed to generate annualized carbon footprint baselines that are directly usable by coffee producers, traders, roasters, and retailers for corporate GHG accounting and climate target setting, rather than as a full life cycle assessment (LCA) of coffee production systems. In line with the GHGP's Corporate Accounting and Reporting Standard, Corporate Value Chain (Scope 3) Standard, Scope 3 Calculation Guidance, and Scope 2 Guidance, as well as Science Based Targets initiative (SBTi) recommendations, results are derived on a per-year basis. This ensures

that the derived baselines can be integrated into annual corporate inventories, procurement-related Scope 3 Category 1 reporting, and progress tracking against climate targets. As such, the study intentionally avoids averaging emissions across multiple production years or cycles, given that averaging is not recommended within corporate GHG accounting frameworks and would obscure year-specific emission profiles that are critical for realistic inventory construction and target tracking.

While results represent a GHG inventory for the reported baseline year, consistent with GHGP and SBTi reporting principles, the study acknowledges that this approach does not explicitly capture inter-annual variability in yields or management intensity (e.g., biennial bearing or renovation phases). This limitation is inherent to annual corporate GHG accounting and inventory-based baselines and is considered acceptable given the study's objective of establishing comparable national-level baselines that support benchmarking and enable reporting. Nevertheless, for the purpose of strengthening long-term monitoring, informing climate strategy development, and improving the reliability of GHG inventories for perennial systems, it is recommended that the sector align on an improved approach whereby emissions can be calculated and reported consistently over multiple consecutive years, with each year assessed separately to capture inter-annual variability in yields, management practices, and plantation age dynamics. This is in line with recommendations from the third-party technical reviewer, CIRAD, as well as other expert reviewers. However, implementing or showcasing such a multi-year assessment approach was beyond the scope of the present study.

2.3. SCOPE OF THE STUDY

2.3.1. SYSTEM BOUNDARY AND FUNCTIONAL UNIT

The system boundary for all analyses conducted in this study is defined at the farm-gate level, consistent with internationally recognized carbon accounting standards and the methodological requirements of the CFP. This boundary encompasses all relevant activities occurring up to the point where a coffee product leaves the farm, expressed per functional unit of kg GBE.

Within this boundary, the study includes:

- Coffee cultivation activities, including input application (e.g., fertilizers) and crop maintenance;
- On-farm processing where applicable (e.g., wet processing, pulp or husk, and wastewater handling, wherever applicable);
- Upstream emissions associated with the production of agricultural inputs such as fertilizers, pesticides, fuel, and electricity;

- Farm-level energy use and machinery operations;
- On-farm residue and waste management practices;
- Transportation from the farm to the first point of sale or aggregation.

Activities occurring beyond the farm-gate, such as centralized milling, export logistics, roasting, packaging, retail, and consumption, fall outside the scope of this baseline study and are therefore not included in the analysis and reported results.

The farm-gate boundary reflects both the study's analytical focus and practical considerations regarding data availability and comparability. It enables a consistent assessment across countries and Supplier Partners, while capturing the dominant emission sources in coffee production systems up to farm gate. The study boundary excludes processing outside the farm-gate, export, roasting, distribution, and retail stages. The results should therefore be interpreted as farm-gate baselines rather than comprehensive country-level carbon footprints of the entire coffee value chain.

2.3.2. PRODUCTION AND GEOGRAPHIC SCOPE

The study covers coffee production in five Latin American countries, including Brazil, Colombia, Honduras, Mexico, and Peru. This section further classifies the scope of analysis within these countries.

Coffee Species

Globally, coffee production is dominated by two species, Arabica (Coffea arabica) and Robusta (Coffea canephora), which differ in their agro-ecological requirements, management practices, yields, and input profiles. As a result, their GHG emission profiles may differ substantially.

In Latin America, coffee production is overwhelmingly dominated by Arabica, which accounts for the vast majority of regional output and export volumes. Consequently, and in line with the objective of establishing representative national farm-gate baselines for the region, this study focuses primarily on Arabica coffee production, with baselines for such production established for Brazil, Colombia, Honduras, Mexico, and Peru.

Brazil, however, represents a specific case within the Latin American context, as it has economically significant production of both Arabica and Robusta. To reflect this structural duality and its relevance for national-level carbon footprint accounting, separate farm-gate baselines were established for both Arabica and Robusta coffee production in Brazil.

As coffee cultivation is highly dependent on suitable climatic and soil conditions, which vary considerably across Latin America, further agro-ecological differences were explicitly accounted for in the study's sampling design (Section 3.5.). However, to

ensure methodological consistency and relevance at the regional scale, baselines were defined only for the coffee species that are materially significant within each country's production system, not for various farm-level production systems. While this approach supports statistical robustness at the national scale, it does not fully capture the diversity of production archetypes (e.g., agroforestry systems) that may exhibit structurally different emission profiles. As noted by CIRAD during the third-party review process, future iterations of such studies could benefit from the development of archetypal baselines that better reflect system-level heterogeneity, provided sufficient sample sizes and statistical stability can be ensured.

Geographic Boundaries

Surveys were deployed in the areas listed in Table 2, based on department-level production data to assign sampling weights. This ensured the proper representation of coffee-growing regions within the study, with assigned samples per region being proportionate to the region's annual coffee production volumes.

COUNTRY	COFFEE TYPE	DEPARTMENTS / STATES	NO. OF DEPARTMENTS	REPRESENTATIVE SHARE
Brazil	Arabica	Bahía, Espírito Santo, Paraná, Rio de Janeiro, Minas Gerais, São Paulo	6	99.5%
	Robusta	Bahia, Espirito Santo, Rondônia	3	95.8%
Colombia	Arabica	Antioquia, Bolívar, Cesar, Magdalena, Caldas, Cauca, Huila, Nariño, Quindío, Risaralda, Santander, Tolima, Valle de Cauca	13	98.7%
Honduras	Arabica	Comayagua, Copán, El Paraíso, Francisco Morazán, Intibucá, La Paz, Lempira, Ocotepeque, Santa Bárbara, Yoro	10	97.7%
Mexico	Arabica	Chiapas, Oaxaca, Puebla, Veracruz, Hidalgo	5	97.7%
Peru	Arabica	Amazonas, Cajamarca, Cusco, Junín, Pasco, Puno, San Martin, Ucayali	8	94.7%

Table 2: Coffee Production Regions in 5 Origin Countries

While the sampling design initially considered additional coffee-producing departments beyond those listed above, certain areas were ultimately excluded due to limited access and other practical constraints, including logistical challenges

related to remoteness and transport, department-level production data availability limitations, safety considerations for field teams in specific municipalities, and other coordination constraints with local partners. In most countries, the excluded areas account for a relatively minor share of national production and did not materially affect overall sample representativeness. In the case of Brazil Robusta, however, the exclusion of Rondônia, an important producing state, did influence the final sample composition. As a result, the Brazil Robusta baseline primarily reflects production systems represented within the sampled regions and should be interpreted within that geographic scope. Maps provided in Figure 3 illustrate the geographic scope of the study, distinguishing sampled regions (dark green) from excluded areas (light green). Further details on sample allocation are presented in Section3.5.1.

BRAZIL - ARABICA

Sampled:
1. Bahia
2. Minas Gerais
3. Espiritu Santo
4. São Paulo

Not sampled:
5. Paraná
6. Rio de Janeiro

BRAZIL - ROBUSTA

Sampled:
1. Bahia
2. Espiritu Santo

Not sampled:
3. Rondonia

COLOMBIA-ARABICA

Sampled:
1. Antioquia
2. Caldas
3. Cauca
4. Huila
5. Nariño
6. Quindio
7. Risaralda
8. Santander
9. Tolima
10. Valle del Cauca

Not sampled:
11. Bolívar
12. César
13. Magdalena

HONDURAS - ARABICA

Sampled:
1. Comayagua
2. Copán
3. El Paraíso
4. Francisco Morazán
5. Intibucá
6. La Paz
7. Lempira
8. Ocotepeque
9. Santa Bárbara
10. Yoro

Figure 3: Maps of focus countries with included and excluded sampling areas

2.4. DATA, TOOL, AND IMPLEMENTATION BOUNDARIES

Several additional boundaries are inherent to the design and implementation of the study and are important for the interpretation of results.

First, data collection relied on Supplier Partner networks and trained enumerators to access farms and conduct surveys. While a structured randomization protocol (Annex 6) was applied, farm selection was constrained to farms within participating supply chains, and complete randomization in accessing farms was not possible. As part of the consultative study design process, Supplier Partners indicated that their teams would only be able to access farms where they already had established commercial linkages. As a result, the dataset largely reflects production systems that are integrated into formal supply chains and may underrepresent farms operating outside these networks.

Second, the study is bound by the choice of calculation tools, primarily the CFP, supplemented by the 4C tool for comparative analysis. CFP was selected by the Consortium Partners as a standardized, science-based tool aligned with Intergovernmental Panel on Climate Change (IPCC) methodologies and widely used in agricultural supply chains. Like all model-based calculators, CFP relies on a combination of primary activity data, default emission factors, and simplified representations of complex biophysical processes. These methodological characteristics constitute an explicit boundary of the study and influence both absolute values and cross-country comparability. Further explanation of the CFP's

methodological characteristics is provided throughout the body of this report as relevant.

Third, certain components of carbon stock change were intentionally excluded from the core analysis, per agreement with the Consortium Partners. In particular, soil organic carbon (SOC) changes, reforestation/deforestation, and land-use change (LUC) emissions were kept out of scope due to methodological readiness and removal reporting considerations. At the time of study implementation, methodologies for estimating SOC and LUC within the CPF were undergoing revision and were not consistently operational. Furthermore, the CFP identifies its reforestation/deforestation module as a Tier 1 approach and advises that it should not be used for reporting removals, further limiting its suitability for inclusion in core reported baseline values. To avoid partial or inconsistent application that could compromise cross-country comparability and reporting integrity, these elements were excluded from the core baseline results. Only carbon captured in newly established non-crop woody biomass (e.g., shade trees, intercrops, hedges) was included. The rationale for these boundary decisions is transparently documented and further discussed in Methodology Section 3.2.

2.5. ANALYTICAL APPROACH AND INTERPRETATION OF RESULTS

All analyses presented in this report were conducted with the aforementioned objectives and boundaries in mind. Results are reported primarily at the national level, with additional disaggregation by emission source, and analytical exploration of variability across farms. The study does not aim to generate farm-level performance rankings or prescribe farm-specific mitigation actions. Instead, it provides aggregated insights into structural emission drivers and typical management patterns within national coffee production systems in Latin America, which may suggest overarching strategic approaches to emission reduction.

Analytical methods, such as Z-score-based hotspot identification and correlation/factor-specific analysis, are used to explore variability and contextualize averages, rather than to identify outliers for exclusion or statistically significant archetypes. The details regarding Z-score analysis are discussed in Section 4.1.2., whereas quality control and exclusion are discussed in Section 3.8.2. Readers should interpret results as standardized, internally consistent estimates suitable for benchmarking, learning, and strategic planning, rather than as precise measurements of emissions at individual farms.

Taken together, the defined scope enables the study to balance scientific rigor, transparency, and practical applicability, while clearly communicating the limitations and intended use of the results.

3. METHODOLOGY

3.1. OVERVIEW

Establishing credible carbon footprint baselines requires a methodological framework that is both scientifically rigorous and practically implementable across diverse coffee production systems. This chapter outlines the methodological approach adopted for the study, to ensure representative, comparable, and robust results that could provide a foundation for future benchmarking and climate action. Overall, the methodology combines statistical precision with field-level practicality, integrating stratified sampling, standardized data collection, and advanced analytical tools. In doing so, it captured the complexity of coffee production systems while also maintaining consistency and feasibility across five countries. The current chapter, describing the methodology, is organized into six key sections:

OPERATIONAL BOUNDARIES AND DATA CATEGORIES	This section defines the system and analytical boundary and outlines the key data categories considered in the study.
CALCULATION METHODOLOGIES	This section provides a detailed overview of the CFP, the tool used for the national farm-gate coffee carbon footprint baseline estimation and the primary tool used for comparative analysis, the 4C Carbon Footprint Add-On.
SAMPLING FRAMEWORK	This section explains the study's stratified sampling design, sample allocation procedures, and randomization protocol, all of which ensured an unbiased and proper representation of coffee-growing regions.
SURVEY DESIGN AND IMPLEMENTATION	This section identifies the data requirements that were included in the survey design and highlights how the survey was developed, tested, and deployed through a digital questionnaire across all countries.
ENUMERATOR TRAINING AND DATA COLLECTION	This section summarizes the measures taken to guarantee consistency, accuracy, and quality during field-level data collection, including enumerator training efforts, ongoing support and communication protocols, and other feedback loops.
DATA CLEANING AND ANALYSIS	This final section describes how the collected field-level data was transformed from raw survey data into standardized, verified, and model-ready inputs for the CFP and the 4C, and later into aggregated and interpreted final results.

Table 3: Methodology Sections

Each of these steps combined empirical rigor with practical execution, ensuring that the resulting baselines would be aligned with internationally recognized standards, while also being truly reflective of the diversity of coffee production systems. This approach allowed for credible benchmarking, and insight into future emissions reduction strategies for the coffee sector.

3.2. OPERATIONAL BOUNDARIES AND DATA CATEGORIES

Data collection was confined to the farm level. Emissions-related data from activities that took place beyond this boundary were excluded. The data points for analysis were selected based on the requirements of the CFP—specifically, the Cool Farm Platform perennials module version 2.0. summarizes the data categories that were included in the survey design, for eventual GHG calculations.

CATEGORY	SUB-CATEGORY	DETAILS
Inputs (Resources and materials used)	General farm-level characteristics	· Country · Climate · Temperatures
	Crop-level inputs	· Area · Age · Tree density · Plantation lifecycle duration · Crop type · Percentage of dead coffee trees · Production volume · Residues · Treatment of dead plants · Organic matter
	Pesticides	· Type · % active ingredient · Application rate
	Fertilizers	· Type · % formulation · Application rate · Origin
	Irrigation	· Type · Water source

		· Amount of water used · Source of power usage
	Energy	· Category (field and processing) · Source (fuel and electricity) · Usage (quantity)
	Machinery	· Type · Fuel type · Number of operations
Processes (Farm and crop management practices)	Waste management	· Seed · Fruit waste (left on tree) · Pruning waste · Leaf litter · Dead plant · Pulp or husk · Wastewater
	Logistics (transport)	· Mode · Weight carried · Distance
	Non-crop estimated	· Intercrop trees · Shade trees · Hedges
Outputs	Wastewater	· Quantity (m³ or L) · Biological Oxygen Demand (BOD) or Chemical Oxygen Demand COD) value · Treatment type
Land Use Change (excluded from the CFP assessment)	Land use change	· Previous state · Year of change · Management inputs

Table 4: GHG calculation requirements under CFP perennials module version 2.0

In collaboration with Consortium Partners, it was agreed that selected components of the CFP would be excluded from the analysis, namely soil carbon changes and reforestation/deforestation. At present, the CFP captures three components: (1) carbon captured in newly planted non-crop woody biomass (such as shade trees, intercrops, or hedge rows established during the current crop cycle); (2) carbon stock changes resulting from reforestation or deforestation; and (3) changes in soil organic carbon associated with land use or management changes. Of these three components, only non-crop biomass changes were included in the analysis, and resulting values represent baseline carbon stocks only, and do not yet quantify sequestration.

Soil carbon changes were excluded because, during project planning and modeling, this part of the CFP perennial crop module version 2.0 was still under development and not yet available as a fully released, project-ready component for perennial systems. Including soil carbon changes would have therefore introduced methodological instability and reduced comparability between countries and supply partners. For this reason, carbon stored in or released from soil due to recent changes in land use or management practices was kept out of scope for the current baseline. It is recommended for future inclusion in similar studies, once the soil carbon changes component of the perennial module becomes fully available and operational.

Furthermore, reforestation effects were not included in the core baseline because the available modeling approach within the CFP is based on a Tier 1 methodology. According to the tool's guidance, this approach does not meet the requirements for reporting removals and is therefore not suitable for inclusion in reported baseline results.

Land conversion is, however, known to induce significant and often long-lasting changes in soil carbon pools (IPCC, 2019[2]; Poeplau et al., 2011[3]). The survey therefore collected national-level Tier 1 data on the year LUC, the previous state of the land, the type of tillage, and the change of management inputs attributable to LUC. The collected data was applied in the 4C tool to derive a high-level estimate of changes in carbon stocks. However, these LUC-related results are not integrated into the core CFP results, and are inclusive of several limitations. Annex 1 illustrates their limitations as well as potential effect on total emission outcomes, while the underlying raw data is available for future analyses where high-level LUC estimates may be required.

3.3. CALCULATION METHODOLOGIES

3.3.1. COOL FARM PLATFORM

The CFP, developed by the Cool Farm Alliance, is a globally recognized science-based tool for calculating carbon emissions and sequestration across agricultural systems. Building on the earlier Cool Farm Tool, CFP provides standardized metrics for GHGs, biodiversity, and water use, grounded in IPCC methodologies and extensive empirical research, and is used to support the measurement, management, and reduction of environmental impacts in farm supply chains. The platform offers multiple modeling pathways, including perennial crops, annual crops, paddy rice, and potato, allowing users to quantify emissions from diverse production systems and model "what-if" scenarios to identify emission hotspots and develop tailored mitigation strategies. For

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[2] IPCC (2019). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories – Volume 4 (AFOLU)
[3] Poeplau, Christopher & Vos, Cora & Don, Axel. (2016). Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and stone content. SOIL Discussions. 1-10. 10.5194/soil-2016-78.

this study, the CFP's perennial crop pathway was used, as it is specifically designed for tree-based, long-living perennial cropping systems such as coffee.

Given the need for alignment around a single tool within this study, Consortium Partners chose the CFP due to its standing as a leading, credible, independent non-profit GHG calculator. Using the CFP also allows this study to build on the body of work from the aforementioned similar study conducted in Indonesia and Vietnam, USAID GIA, which also used the CFP. In addition, CFP is designed to balance scientific robustness with practical usability, enabling farmers and supply chain actors to input key production data such as crop yield, growing area, fertilizer type and application rate, crop protection practices, energy use, and transport information, in order to generate consistent and transparent carbon footprint outputs.

As with any model-based calculator, CFP embeds several methodological assumptions and parameterization choices. These include default emission factors, simplified representations of biophysical processes, and generalized relationships between management practices and emission outcomes. Even when fully aligned with IPCC principles and when running identical activity data, different parameterizations within the tool may yield divergent emission estimates due to variations in model structure and underlying assumptions. Consequently, CFP results should be interpreted as standardized, internally consistent estimates rather than as absolute measurements of farm-level emissions.

Importantly, this limitation is inherent to all farm-scale carbon accounting tools and underscores the importance of transparency regarding tool choice, scope, and modeling assumptions when comparing results across studies, or when using results to inform mitigation strategies. This study deliberately applies a widely used, standardized tool by design, despite any inherent trade-offs in its site-specific realities. While country-specific or site-calibrated methodologies can provide higher-resolution estimates, they do not readily support cross-country comparability or the evaluation of trends over time by practitioners.

3.3.2.   4C CARBON FOOTPRINT ADD-ON

The 4C Carbon Footprint Add-On, developed by 4C Services GmbH, enables farmers, cooperatives, and production companies to calculate and manage GHG emissions across coffee supply chains using a rigorous, science-based methodology. It relies on primary data, defines clear system boundaries from farm to export (with optional inclusion of final buyers), and ensures full traceability through digital integration in the 4C Portal. The 4C tool aligns with internationally recognized standards such as ISO 14067, the GHGP, PAS 2050, SBTi, and IPCC guidelines. It provides a calculation methodology and framework that any user can apply to develop an individual calculator tailored to their set-up and scope of assessment.

A comparative analysis was conducted with the 4C tool, using the same farm-level dataset, system boundary, and functional unit that was used with the CFP. This parallel application allowed differences in results to be attributed to modeling structure, emission factors and embedded assumptions rather than input variability. The comparison served as a robustness check, assessing general alignment in overall emission magnitudes and key hotspots. This comparative approach helped strengthen transparency and supported informed interpretation of tool-based differences in GHG results.

3.4. SAMPLING FRAMEWORK

The study's sampling framework was designed to produce statistically robust representative national farm-gate coffee carbon footprint baseline estimates, while ensuring methodological consistency and comparability across five origins. To reflect the spatial distribution of coffee production, the sampling design employed regional production patterns, with samples allocated across major production areas within each country. This approach ensures that the resulting baselines represent the diversity of production contexts while remaining aligned with the overall structure of national coffee production. At the farm level, key agronomic, environmental, and processing variables were collected to characterize production systems and support subsequent analyses of system-level differences and drivers of variability.

3.5. SAMPLING APPROACH

To ensure statistical significance, GHGP[4] recommends a minimum of 370 samples per country, based on homogeneous farm characteristics, a 95% confidence interval, a 5% margin of error, and a 0.5 population proportion. However, coffee production systems in the target countries are heterogeneous across environmental and management dimensions. Therefore, relying solely on the minimum GHGP requirement risks underrepresenting certain production contexts.

To address this, the sampling design incorporated a heterogeneity analysis, resulting in a heterogeneity-informed adjustment to the baseline sample size. Seven identified key drivers of variability in coffee production systems were considered: climate, soil type, farm size, LUC, fertilizer use, coffee processing, and agroforestry practices. This set of drivers was refined with input from the third-party reviewer, as was the approach to the heterogeneity analysis overall. Specifically, the analysis was performed in the context of a literature review, and each of the characteristics was quantitatively assessed across countries using a using a four-tier scale—high variability, high-

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[4] Greenhouse Gas Protocol. (2022). Appendix A: Emission factors from cross-sector tools. World Resources Institute. https://ghgprotocol.org/sites/default/files/2022-12/AppendixA.pdf

moderate variability, moderate variability, and low variability—to represent the degree to which coffee production systems were heterogenous, considering the seven aforementioned drivers. The list of resources used for heterogeneity analysis is provided in Annex 5. Ultimately, the assessment served as a conservative, expert-informed approach to adjust the total sample size beyond the GHGP minimum. It was not used to define statistical strata or to estimate typology shares, but rather to reduce the risk of under-representation of diverse production systems. Final sample sizes for each country and coffee species were therefore calibrated to (1) meet or exceed the GHGP minimum requirement, and (2) provide additional, precautionary coverage in countries where greater production system diversity was expected based on literature and expert knowledge.

To allocate samples across regions, department-level coffee production volume data was used as the primary weighting factor. For full transparency, a detailed list of the secondary data sources used to determine production shares is provided in Annex 4. Although municipal-level data could, in principle, provide a higher level of detail, department-level data were chosen because (1) they were more consistent and accessible across all five countries, ensuring comparability, and (2) department-level granularity provided a more practical basis for field implementation (i.e., it allowed the study to avoid sampling in hard-to-reach areas for enumerators, particularly those with insignificant production). To preserve randomization and avoid sampling bias, and to align with enumerator capacity, sample requests were assigned regardless of archetype classification. Factor-specific analyses related to these archetypes (e.g. fertilizer use), were conducted post-data collection. The department-level stratification approach thus struck an optimal balance between methodological robustness and operational feasibility.

Overall, the study's adaptive sampling framework builds on the statistical foundation of the GHGP and further refines the sample size to capture the diversity of production conditions. The approach ensures the representativeness, comparability, and reliability of the resulting national farm-gate coffee carbon footprint baseline results, as it integrates a heterogeneity-driven adjustment process, department-level stratification, and robust sample allocation.

3.5.1. SAMPLE ALLOCATION

Sample sizes per region were calibrated to ensure representative coverage of coffee production systems at both national and regional levels, based on production volumes. Departmental targets proportional to each department's share of national coffee production were communicated to Supplier Partners, who in turn proposed sampling in specific municipalities where they had capacity, and indicated the number of farms they could realistically cover. This collaborative mechanism allowed for iterative refinement until departmental targets were met as closely as possible, and it further ensured that Supplier Partners could be assigned to different municipalities, avoiding that farms were surveyed twice. Where access limitations prevented attainment of the minimum sample size thresholds required for a statistically robust baseline, additional enumerators were contracted to address substantial data gaps in key production regions. In the rare case that these additional efforts were still insufficient to close remaining gaps, a three-step hierarchical gap-filling strategy was applied, consisting of the following approaches:

1. **Bootstrapping**: Random duplication of valid observations, full surveys, or data points within the same department to meet sample targets.

2. **Borrowing:** If bootstrapping was not feasible, missing samples were filled using data from departments with similar agroecological and production characteristics.

3. **Exclusion:** Where neither option was viable due to high heterogeneity and lack of data, the department was excluded from the sample and subsequent analysis.

Based on these measures, Cesar, Magdalena, and Bolívar in Colombia; Paraná and Rio de Janeiro in Brazil (Arabica); and Hidalgo in Mexico were excluded from the sample and subsequent analysis. Each of these departments represents minimal shares of national production and is unlikely to introduce substantial bias to the study's results. Rondônia in Brazil (Robusta) was excluded from the study scope due to limited access to farms in the region. As Rondônia accounts for nearly one-fifth of Brazil's Robusta production, the national farm-gate baseline for Robusta coffee production must be interpreted with some caution. Overall, however, by combining statistically informed departmental targets with a transparent, stepwise gap-filling procedure, the sample allocation process achieved broad geographic coverage while maintaining methodological integrity.

In parallel to the regional and departmental allocation procedures described above, the achieved sample sizes in all countries exceeded the minimum thresholds required

for statistical robustness. As part of the final data-quality screening, a limited number of individual farm surveys were excluded where values were identified as clearly implausible or inconsistent with realistic agronomic conditions. In total, 6 farms in Brazil (Arabica), 14 farms in Brazil (Robusta), 37 in Honduras, 41 in Mexico, and 10 in Peru were removed from the final dataset, while no exclusions were necessary in Colombia. Exclusions were primarily related to yields falling well outside plausible ranges or to clearly unrealistic input levels, particularly for fertilizer application or machinery use. This targeted cleaning step was applied conservatively and serves to reduce the influence of extreme observations, thereby ensuring that the final results are representative of typical production practices within each coffee-growing region. Further details regarding quality control assessments are discussed in Section 3.8.2. Table 5 presents the final sample allocation by country and department, along with the number of bootstrapped samples.

COUNTRY	COFFEE TYPE	COUNTRY-LEVEL SAMPLE NUMBER	DEPARTMENT	DEPARTMENT-LEVEL SAMPLE NUMBER	BOOTSTRAPPED SAMPLE NUMBER
BRAZIL	Arabica	500	Bahia	9	0
			Espirito Santo	33	0
			Minas Gerais	406	5
			Sao Paulo	52	0
	Robusta	371	Bahia	69	0
			Espirito Santo	302	0
COLOMBIA	Arabica	600	Antioquia	67	0
			Caldas	46	0
			Cauca	84	0
			Huila	137	0
			Nariño	57	0
			Quindío	7	0
			Risaralda	41	0
			Santander	25	0
			Tolima	109	0
			Valle del Cauca	27	0
HONDURAS	Arabica	601	Comayagua	122	0
			Copan	96	3
			El Paraiso	98	0
			Francisco Morazan	8	0

			Intibucá	40	0
			La Paz	50	3
			Lempira	90	2
			Ocotepeque	52	0
			Santa Babara	20	0
			Yoro	25	5
MEXICO	Arabica	605	Chiapas	288	0
			Oaxaca	7	0
			Puebla	140	0
			Veracruz	170	1
PERU	Arabica	620	Amazonas	69	0
			Cajamarca	159	0
			Cusco	52	0
			Junin	159	0
			Pasco	49	0
			Puno	5	0
			San Martin	88	0
			Ucayali	39	0

Table 5: Sample allocation at country and department level

3.5.2. RANDOMIZATION STRATEGY

Randomization was a cornerstone of the sampling design, ensuring that farm selection for on-site data collection remained unbiased and representative of the diversity of coffee production systems within each country. To operationalize this principle, a randomization protocol (Annex 6. RANDOMIZATION PROTOCOL was developed and shared with Supplier Partners and enumerators, providing clear, actionable guidance for sampling implementation. One key principle of the randomization protocol was the diversification of visits. Enumerators were asked to prioritize sparsely-located farms to reduce clustering and broaden the range of production contexts. While enumerators could use previously-surveyed farms as reference points for identifying additional candidates, they were instructed to avoid selecting farms with close relationships or highly similar characteristics (e.g., same family ownership) to minimize bias from overrepresentation.

Enumerators were also encouraged to ensure representation of both certified and non-certified farms, where applicable, rather than disproportionately sampling certified farms—or farms participating in similar interventions—due to their greater visibility in supply chains. This practice was to maintain a balanced data set that would accurately reflect the full spectrum of production systems. Adherence to the

randomization protocol was emphasized as critical for preserving the validity of the baseline, and enumerators were provided with structured guidance. However, absolute adherence was challenged by farm access (i.e., farmers needed to provide consent in order to be surveyed) and ultimate compliance with the randomization protocol could not be independently verified. In practice, Supplier Partners reported that they were unable to visit farms outside their established supply chains, and many of their supply chains provided interventions. This reality stood in contrast to USAID GIA in Vietnam and Indonesia, where broader access was feasible and Supplier Partners were able to visit farms outside their value chains. Consequently, farm selection cannot be considered fully random, as Supplier Partners proposed candidate farms, and the sample was restricted to farms within participating supply chains. This introduces a potential source of selection bias, as farms outside these networks or with weaker market integration may not be properly represented. While the randomization protocol was designed to mitigate bias within these operational constraints, the resulting dataset should still be understood as representative of participating supply chains. Accordingly, the results presented in this study should be interpreted in light of this limitation.

3.6. SURVEY QUESTIONNAIRES

MCS sought to design a survey instrument that would be concise, user-friendly, and efficient, while meeting all data requirements for the CFP. Consortium Partners recommended that the questionnaire not exceed two hours in length; guided by this suggestion, MCS developed an initial time-sensitive draft, focusing on essential data fields. The survey underwent multiple feedback rounds, incorporating feedback from the study's third-party reviewer as well as suggestions from Supplier Partners. This process improved survey robustness, clarity, and practicality.

Questions and response formats were crafted in plain, straightforward language, recognizing varying levels of enumerator and farmer experience. The survey was initially drafted in English, then carefully translated into Brazilian Portuguese and Latin American Spanish. Enumerators also received a detailed guidance manual with step-by-step instructions for interpreting questions and handling uncertainties, which complemented the intensive live online training sessions conducted prior to survey application.

3.6.1. SURVEY DESIGN PROCESS

To ensure that the collected data would be scientifically robust and aligned with CFP requirements, MCS followed a three-part approach: 1) mapping the data requirements, 2) developing the survey, and 3) creating a digital tool to deploy the survey.

3.6.1.1. IDENTIFICATION OF DATA REQUIREMENTS AND SURVEY DEVELOPMENT

To begin, MCS conducted a thorough review of the CFP requirements and created a comprehensive data matrix in Microsoft Excel that covered inputs, outputs, management practices, land use, and other aspects relevant to both carbon accounting and sustainability assessment (Section 3.2).

Each data requirement was converted into a clear, farmer-friendly question, while preserving methodological consistency with CFP definitions and calculation logic. As one example, given that several CFP input fields (e.g., fertilizer quantities, fuel use, etc.) are difficult for some farmers to report directly due to measurement limitations, unfamiliar units, or recall constraints, many CFP data requirements were operationalized as sequences of simpler, intermediate questions. In this case, rather than asking farmers to report fertilizer application rates directly in kg per hectare (ha), the survey collected information on the number of bags applied, bag size, and application frequency, which were then converted into standardized units. Excel was selected as the design environment to allow such systematic structuring of questions, variables, units, response options, and validation logic, and to ensure full scientific traceability between survey inputs and the underlying CFP model parameters.

Before finalization, the draft survey was shared with Consortium Partners and technical stakeholders (including CIRAD) for technical review and practical feedback. The survey was then refined to reflect their input, ensuring both scientific robustness and field-level feasibility. Once finalized, the Excel master survey was transferred into KoboToolbox for digital deployment, where all survey logic, skip patterns, variable constraints, and validation rules were implemented. This included mandatory fields for critical parameters, GPS location capture, automated flagging of values outside predefined ranges, and conditional question flows based on previous responses. These controls ensured data completeness, internal consistency, and high data quality across all participating countries. The Excel-based master survey thus served as the blueprint for the digital survey architecture used for large-scale field data collection.

At the same time, it is acknowledged that survey design itself represents a significant source of variability when applying CFP or similar standardized methodologies. Different organizations may operationalize identical CFP variables through different question formats, units, or levels of disaggregation, which can influence farmers' ability to respond accurately and consistently. This variability in response quality is an inherent challenge in farm-level carbon footprinting and is not specific to this study. The present approach deliberately adopted a widely used, standardized tool and survey framework by design, and thus reflects the type of data collection and uncertainty that supply chain actors encounter in practice when using such tools. While more localized or bespoke methodologies could, in some cases, improve

precision, they would limit cross-country comparability and comparability across supply chain initiatives, and would likely imply much more costly and time-intensive data collection.

Enumerator Entry	Información del Enumerador
First name and surname of the enumerator conducting the survey	Nombre y apellidos del encuestador
Which participating supplier partner has employed you as an enumerator? In case of others, enter the name of the supplier partner.	¿Qué socio proveedor participante le ha contratado como encuestador? En caso de "otros", introduzca el nombre del socio proveedor
Have you reached the randomized farm location?	¿Ha llegado a la ubicación aleatoria de la finca?
Please record your current location	Por favor, registre su ubicación actual (Si la parcela no está exactamente en la misma ubicación que la casa del productor, pero la encuesta se realiza en la casa del productor, se pueden usar las coordenadas de la casa)
You must reach the randomized farm location to start the survey. Once you reach the location, please click on the 'back' button and answer the question with 'Yes' to	Debe llegar a la ubicación seleccionada de la finca para iniciar la encuesta. Cuando llegue al lugar, haga clic en el botón "Atrás" y responda a la pregunta con un "Sí"para continuar.
Start the survey	Iniciar la encuesta
Which supplier partner does the farm belong to?	¿A qué socio proveedor pertenece la finca?
In case of others, enter the name of the supplier partner.	En caso de "otros", introduzca el nombre del socio proveedor.
Introduction	Introducción del proyecto
We are conducting a research about coffee produced in different regions of Latin America. I would like to visit your farm and some questions about the farming practices that you employ in the field. We have a standardised survey format and it will take around an hour to complete the survey. Your responses will greatly aid our research and your personal details will remain confidential.	Estamos realizando una investigación sobre el café producido en diferentes regiones de América Latina. Me gustaría visitar su finca y hacerle algunas preguntas sobre las prácticas agrícolas que emplea en el campo. Tenemos un formato de encuesta estandarizado y tardará alrededor de una hora en completarla. Sus respuestas serán de gran ayuda para nuestra investigación y sus datos personales serán confidenciales.
Are you interested in participating in the survey?	¿Está interesado en participar en la encuesta?
The farmer is not interested in participating. End the survey, document the rejection of the farmer and move to the next randomised location	El productor no está interesado en participar.Documente la denegación, finalice la encuesta y pase al siguiente lugar aleatorio.

Figure 4: Abstract of the master questionnaire with English and Spanish entries

3.6.1.2. SURVEY DEPLOYMENT VIA KOBOTOOLBOX

To facilitate the efficient collection of data across multiple countries and farm contexts, the Excel survey was digitalized using KoboToolbox, a widely used open-source online platform for field data collection. Specifically, the Excel questionnaire was converted into a structured survey form that is compatible with the KoboToolbox (XLSForm standard). Built-in data validation techniques, mandatory fields, and conditional logic were also applied to reduce entry errors and ensure data completeness at the point of collection. Enumerators were trained to use the mobile interface, which enables offline data-capture in remote farming areas; automatic synchronization occurs once internet connectivity is available. Through this process, MCS built a scientifically-grounded, operationally-practical and digitally-enabled survey instrument that could ensure the integrity, consistency, and completeness of the data collected for the study.

3.6.2. SURVEY TESTING

Prior to deployment in the field, the questionnaire underwent a structured testing and refinement phase to ensure clarity, accuracy, and usability. A trial run was conducted with enumerators and a small sample of farms to evaluate the effectiveness of the wording and sequencing of the questions as well as the skip logic. Feedback from this testing phase was systematically collected and analyzed to identify any ambiguities or culturally-sensitive terminology that could lead to misinterpretations. Based on these insights, the questionnaire was iteratively refined. MCS adjusted certain phrasing for clarity, simplified technical language where necessary, and reorganized sections to improve logical flow and reduce respondent burden. Additional validation checks and response constraints were implemented to further enhance data quality; for example, fertilizer application rates were restricted to agronomically-plausible ranges, and GPS location capture was required to verify farm boundaries and production regions. These measures helped to minimize entry errors, reduce outliers caused by unit confusion, and ensure internal consistency across all survey responses.

3.6.3. SURVEY IMPLEMENTATION AND MONITORING

Survey execution and follow-up procedures were designed to ensure consent, consistency, and data reliability across origins. When conducting on-site farm visits, trained enumerators first obtained informed consent from each participant. A signed consent form provided at the start of the survey served as a formal agreement of farmer participation. During the data collection process, enumerators captured both quantitative and qualitative information, supported by built-in validation rules and skip logic to minimize entry errors. To further maintain oversight and data integrity, MCS monitored submissions weekly, identifying anomalies and providing feedback loops for corrective action if immediate responses were needed. This approach ensured that data was collected in a consistent, verifiable, and scientifically robust manner across all farming contexts.

3.7. TRAINING OF ENUMERATORS

As mentioned, to further guarantee data quality, consistency, and reliability, enumerators participated in comprehensive training prior to survey application. This training, led by MCS in Brazilian Portuguese and Latin American Spanish, consisted of three steps and sought to familiarize trainees with the study and survey objectives, its methodological frameworks, and expectations in the field. MCS emphasized the critical role of enumerators in safeguarding data accuracy and guiding respondents.

- **Step 1:** Over the course of a half-day of virtual training, MCS introduced enumerators to the objectives of the survey and conducted a deep-dive

explanation of the installation and use of KoboToolbox. Enumerators learned how to download the questionnaire and conduct a trial run.

- **Step 2:** Enumerators were asked to conduct a field visit to practice a trial run of the questionnaire. This allowed them to have hands-on experience with data collection and submit sample surveys. It also allowed them to evaluate time requirements and confirm the technical functionality of the digital tool.

- **Step 3:** Following a review of the submitted sample surveys, MCS led a virtual discussion about the data collection experience and flagged any technical issues that they identified within enumerators' data entries. Enumerators discussed common challenges identified during their trial exercises, and MCS provided corrective guidance to minimize errors during subsequent fieldwork.

To reinforce capacity and provide ongoing support, enumerators received additional and complementary training materials following the virtual sessions, including session recordings and written guidance documents. Dedicated WhatsApp groups were also established for each country, enabling real-time communication and rapid resolution of queries during the data collection phase.

Figure 5: Exemplary content of enumerator training materials

3.8. DATA COLLECTION

Accurate and comprehensive data collection is fundamental to producing reliable carbon footprint baseline estimates. Only high-quality data can ensure robust calculations. To achieve this, the data collection process relied on timely planning, continuous monitoring, and regular feedback loops, supported by strong coordination between enumerators, Supplier Partners, and MCS. Multiple communication channels were leveraged to keep all stakeholders informed and address challenges promptly.

In parallel with these data gathering exercises, strict data protection and confidentiality requirements were applied throughout the data collection and processing phases. All farm-level data were collected and handled in compliance with applicable data protection regulations, including the General Data Protection Regulation (GDPR). Personal identifiers and directly traceable information were excluded from the analytical dataset, and each farm was assigned a unique, anonymized identifier to prevent re-identification. Access to raw survey data was restricted to authorized project partners only, and data were stored on secure servers with controlled access rights. Data sharing with Consortium Partners was limited to an aggregated overview of the progress of the study, ensuring that no individual farm details or any other confidential information was shared. These measures were implemented to safeguard farmer confidentiality, prevent misuse of information, and ensure that the dataset could be reused responsibly for future analyses without compromising the anonymity of participating farms.

3.8.1. TIME SCHEDULE AND FIELD TEAM MANAGEMENT

Data collection was conducted between October 2024 and September 2025 across the five target countries: Brazil, Colombia, Honduras, Mexico, and Peru. As possible, the timeline aligned closely with each country's harvest calendar to ensure farmer-provided data best reflected a representative production year (i.e., to reduce time between the practice and related reporting). As possible, enumerators were asked to visit farms during the post-harvest period to capture accurate records of management practices, input use, and processing methods, after obtaining informed consent.

3.8.2. QUALITY PROCESS AND COMMUNICATION

Supplier Partners oversaw their own enumerator deployment and identified country-level leads to support project coordination. While each enumerator joined the appropriate WhatsApp group for ongoing technical support, only the country-level lead received bi-weekly monitoring reports on survey submissions. These reports, prepared by MCS, enabled structured progress tracking, identification of potential data gaps, and timely follow-up, including targeted feedback to improve data completeness and consistency.

As surveys were submitted, datasets underwent a systematic quality control (QC) process managed by MCS to ensure validity, accuracy, and internal consistency. The QC process combined statistical screening with plausibility and coherence checks. First, anomalies such as outliers, missing observations, and irregular distributions in key variables (e.g., farm size, yield, and input use) were identified using a Z-score analysis. All input parameters and emission categories were evaluated, with standardized deviations calculated relative to the sample mean. Screening was conducted not only on individual input and output variables (e.g., kg, liters), but also on emission intensities per ha and per kg of GBE. Observations falling outside the predefined threshold of −2 to +2 standard deviations were flagged for further review. Detailed methodological information on the Z-score computation and interpretation is provided in Section 4.1.2.

In parallel, logical consistency checks were conducted to verify coherence across responses. For example, reported fertilizer quantities were cross-checked against transport volumes, and total inputs were validated relative to farm size and reported production volumes. Responses were also assessed against literature-based plausibility ranges to ensure alignment with scientifically-established reference values for similar production contexts. In total, six key data categories were screened using this combined statistical and plausibility-based approach.

3.8.2.1. DETAILS ON RESIDUE-SPECIFIC QC

During coffee production, it is important to note that substantial by-products are generated; typically, 30-50% of the weight of coffee fruit becomes waste[5]. These waste residues (primarily pulp and husk) undergo various residue and waste management treatments, and waste is also produced as a result of pruning biomass, leaf litter, and dead trees. Coffee pulp typically constitutes approximately 26-30% of cherry dry weight (or around 43% of fresh cherry weight), while mucilage, hulls, and parchment account for the remaining by-product fraction[6]. These literature-based proportions were used to validate farm-reported residue quantities by cross-checking against reported cherry production volumes. Reported values were then screened against mass-balance expectations to identify inconsistencies between production output and residue generation, and any deviations beyond plausible ranges were flagged for review.

The pruning residues were further assessed using established reference values, with young stands typically generating 1-3 kg of biomass per tree and mature stands

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[5] Hoseini, Marziyeh, et al. "Coffee By-Products Derived Resources. A Review." Biomass and Bioenergy, vol. 148, May 2021, p. 106009, https://doi.org/10.1016/j.biombioe.2021.106009

[6] Heuzé V., Tran G., 2015. Coffee hulls, fruit pulp and by-products. Feedipedia, a programme by INRAE, CIRAD, AFZ and FAO. https://www.feedipedia.org/node/549 Last updated on May 11, 2015, 14:33

generating 5-12 tons per ha, per pruning event, generally occurring every 5-6 years[7]. Reported quantities were further evaluated against planting density and total farm area to ensure structural plausibility and to identify values inconsistent with expected biomass outputs.

Litterfall benchmarks were derived from peer-reviewed studies covering both monoculture and shaded coffee systems, providing reference values for expected above ground biomass turnover. In parallel, dead tree fluxes were estimated from farm reported counts or weights using an average dry biomass of approximately 15 kg per mature plant. To ensure a full picture, reported mortality rates exceeding 15-20% were flagged as implausible, so that the reported litter management practices were evaluated against expected biomass generation ranges under comparable agro-ecological conditions[8].

3.8.2.2. DETAILS ON WASTEWATER-SPECIFIC QC

For wastewater, stage-specific benchmarks were used to break down the assessment, emphasizing that treatment conditions (aerobic vs. anaerobic) primarily drive CH_4 formation. The benchmarks are showcased in the table below:

TYPE OF PRODUCT	RANGE
Fresh cherry	≈0-20 L per kg
Wet parchment,	≈0-15 L per kg
Dry parchment/green beans	≈0-10 L per kg

Table 6: Wastewater volume benchmarks for coffee production[9]

3.8.2.3. DETAILS ON AGRICULTURAL INPUTS SPECIFIC QC

Pesticide; nitrogen, phosphorus, and potassium (NPK); and mineral fertilizer inputs were checked for numeric integrity, agronomic plausibility (e.g., unusually low or high application rates), and consistency with reported nitrogen content. This was performed by cross-checking the documented values against values from scientific literature mentioning the importance of mineral nutrition and fertilization in coffee production[10]. Any deviations from expected values within the analysis were flagged

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[7] Gil-Gómez, J. A., Florez-Pardo, L. M., & Leguizamón-Vargas, Y. C. (2024). Valorization of coffee by-products in the industry, a vision towards circular economy. Deleted Journal, 6(9). https://doi.org/10.1007/s42452-024-06085-9

[8] Mendoza Martinez, Clara Lisseth, et al. "Characterization of Residual Biomasses from the Coffee Production Chain and Assessment the Potential for Energy Purposes." Biomass and Bioenergy, vol. 120, Jan. 2019, pp. 68–76, https://doi.org/10.1016/j.biombioe.2018.11.003.

[9] Van Rikxoort, H., Läderach, P., & Van Hal, J. (2012). The potential of Latin American coffee production systems to mitigate climate change. In Climate change management (pp. 655–679). https://doi.org/10.1007/978-3-642-31110-9_43

[10] Mineral nutrition and fertilization. Martinez et al., 2019. In: Coffee: Production, Quality and Chemistry. Farah, A. (eds). The Royal Society of Chemistry 2019.

and reported for clarification. In many cases, discrepancies could be explained by reasonable operational factors, such as the use of organic fertilizers.

3.8.2.4. DETAILS ON IRRIGATION SPECIFIC QC

The irrigation entries were validated against regional practice, which are in usual cases approximately around 94,000 liters per ha per week, and the water-efficient systems using around 400 to 1,000 liters per tree per irrigation event (e.g., modern systems in Brazil case studies). Values which are far outside the typical ranges were flagged[11][12].

3.8.2.5. DETAILS ON TRANSPORT SPECIFIC QC

Transportation was reconciled via a mass balance approach without any reference to literature. For inbound logistics, the total weight of all input materials was aggregated and converted to tons to establish expected transport flows. Outbound transport was benchmarked against the quantity of coffee available at the farm gate, with adjustments made in cases where farmers reported sales from stored product from previous harvest seasons and/or to the selling of outdated stock that had remained unsold.

Overall, throughout the assessment, reported values were iteratively compared with default ranges, and were only considered in the analysis if they were within range, or if there was reasonable justification to maintain the values given internal consistency with literature-based benchmarks. Any flagged observations were compiled into final QC reports and returned to Supplier Partners for verification and correction. This end-stage iterative validation was conducted through email exchanges and virtual meetings, most often facilitated in Brazilian Portuguese and Latin American Spanish by native-speaking team members to ensure effective communication and context-specific clarifications. Enumerators were instructed to verify flagged entries by consulting farmers or revisiting records, creating a continuous improvement loop between collection and validation. Common triggers for revision included incomplete consent forms, implausible input quantities, missing geolocation data, and inconsistencies in auxiliary variables (e.g., shade level, irrigation). Communication for corrections was additionally streamlined through WhatsApp groups, email, and follow-up virtual meetings, ensuring rapid resolution and uniform decision-making across countries.

When no reliable or verifiable site-specific data were available, literature-derived values served as the final reference point. In addition, as mentioned previously, across

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[11] Wikifarmer. (n.d.). From rainwater harvesting to irrigation of coffee trees. https://wikifarmer.com/library/en/article/from-rainwater-harvesting-to-irrigation-of-coffee-trees
[12] It, C. (2017). Best practices for water resources use in Brazilian coffee crops. Cecafé. https://www.cecafe.com.br/en/sustainability/articles/best-practices-for-water-resources-use-in-brazilian-coffee-crops-20170411/

all categories, the Z-score approach was applied, which screened for outliers. Where the number of records exceeded minimum sample needs, unresolved implausible records were excluded to protect representativeness, with exclusions documented by country.

3.8.3. CHALLENGES IN DATA COLLECTION

Despite strong coordination, challenges emerged during the data collection process, which a QC process could not control. These included challenges under the following categories.

- **Logistical**: Difficult terrain, poor road infrastructure, and adverse weather conditions delayed access to some remote farms, which were prioritized under the randomization protocol. Security concerns occasionally required substituting desired sampling locations with nearby farms under the same criteria.

- **Technical**: Limited internet connectivity hindered immediate data synchronization via KoboToolbox; however, this was anticipated during enumerator training and mitigated by offline data collection functionality, automatic synchronization, periodic backups, and providing ongoing technical support on WhatsApp. Enumerators were specifically trained on offline workflows and data-saving procedures to minimize the risk of data loss and ensure continuity in areas with unstable connectivity.

Proper response to these challenges highlighted the adaptability and professionalism of enumerators, whose efforts ensured that the final dataset met rigorous standards for reliability, scientific integrity, and data governance.

3.9. FINAL DATA CLEANING AND ANALYSIS

In addition to the QC process mentioned above, all raw survey data underwent a final systematic cleaning, standardization, and cross-verification process to guarantee data completeness and coherence. This stage transformed the initially diverse survey inputs into a structured, analysis-ready format while maintaining data integrity. While close coordination between MCS, Supplier Partners, and enumerators enabled early identification of potential discrepancies, to ensure further harmonization of all data streams, the following key steps were undertaken before final data integration into the modeling tools.

3.9.1. SURVEY VALIDATION

Only surveys that were complete and included a signed consent form were identified as retainable for analysis. For surveys to qualify, enumerators had to conduct in-person

visits to farms, obtain the farmer's informed consent through written and signed documentation, and confirm that the farms cultivated the relevant coffee type, primarily Arabica in most geographies, and both Arabica and Robusta in Brazil. Surveys completed in less than 20 minutes were excluded, as this time was deemed insufficient to conduct a complete and accurate survey, given the number of questions and the level of detail required to ensure comprehensive and reliable data. Surveys that did not meet these conditions of informed consent and thorough farm visitation were systematically excluded to maintain the accuracy, quality, confidentiality, and representativeness of the final dataset.

3.9.2.   TRANSLATION AND STANDARDIZATION

To ensure cross-country comparability and analytical consistency, some survey responses recorded in local languages were translated into English for the purposes of interpretation and mapping to standardized input categories required by the CFP. This process focused on specific agronomic and contextual terminology (e.g., local tree species names, fertilizer brands, and management practices) and was carried out without modifying the original reported values or underlying responses, which were retained in their original language and format in the raw dataset. Translation was supported by local enumerators and technical reviewers to minimize misclassification of locally-specific practices.

Following such harmonization, the dataset was further streamlined to improve analytical robustness. Non-relevant variables in the context of some of the farms, such as irrigation and on-farm processing activities that were explicitly reported as not applicable for a given farm, were taken out of the modeling dataset to prevent the inclusion of structurally irrelevant information. This cleaning and standardization process enabled a consistent, high-quality dataset suitable for reliable import into the CFP, and ensured methodological comparability across countries, Supplier Partners, and production systems.

3.9.3.   AGGREGATION AND STRUCTURING

Once all data were validated at the individual farm level, all survey responses were consolidated into a standardized master spreadsheet, designed specifically to support bulk upload in the CFP. The dataset was structured using a uniform perennial schema aligned with the input requirements of the CFP. Each row represented a single farm, while columns corresponded to standardized variables, such as farm location, production area, yield, fertilizer type and application rate, crop protection practices, energy use, residue management, transport distances, and agroforestry characteristics.

To ensure traceability and facilitate partner-specific quality checks, the master dataset was organized using hierarchical identifiers, including country, Supplier Partner, region, and farm ID. This structure enabled systematic verification of completeness (missing values), internal consistency (unit coherence and logical relationships among variables), and value plausibility (range and outlier checks against literature benchmarks).

At this stage, aggregation was not only a data consolidation exercise but also a critical data engineering step that ensured compatibility with the variable formatting, unit conventions, and schema requirements of the CFP. The resulting structured dataset provided a harmonized and analysis-ready input file that could be directly ingested into the proper modeling environment, while preserving full traceability back to the original farm-level survey records.

3.9.4. CREATION OF DERIVED VARIABLES

From the verified primary aggregated and structured dataset, a series of derived indicators were generated to support subsequent analytical stages. These included yield per ha, input use intensity, and specific details pertaining to fertilizer and pesticide application across different production systems. The development of these derived variables enabled a more nuanced interpretation of on-farm practices and resource utilization patterns. Moreover, these indicators served as the core analytical inputs for calculating farm-level carbon footprints and facilitated cross-regional comparability of performance metrics within and across coffee production systems.

3.9.5. STANDARDIZING "UNKNOWN" VALUES

Non-outlier responses that nonetheless lacked clarity or completeness were systematically reviewed and, where possible, verified through follow-up exchanges with Supplier Partners and enumerators. Where data gaps could not be resolved at source, transparent and conservative standardization procedures were applied based on CFP documentation, literature references, regional datasets, or expert judgement, in line with established LCA practice. The specific data fields affected, and the corresponding assumptions or standardization rules applied, are described in detail below.

- **Perennial Crop Yields:** A default yield curve based on plant age, as specified in Table 3.2 of the CFP, was used to populate relative annual percentage yield fields.
- **Pesticide Active Ingredients:** When concentrations were unknown, standardized default percentages were assigned from a predefined reference list (Annex 7).

- **Fertilizer Production Origin:** Missing manufacturing locations were assigned based on the most commonly reported production region for that specific fertilizer type within the dataset.
- **Fertilizer Manufacturer Information:** Where fertilizer brand names were provided instead of fertilizer type used, publicly available manufacturer information was consulted to verify likely origins and percentages.
- **Transportation:** Where inbound transport distances were not reported, values were imputed using the median distance calculated from farms within the same country that had disclosed this information.
- **Machinery operations:** Where number of operations were not reported, missing operation frequency data were replaced using median values derived from valid responses.
- **Machinery soil type:** Where soil type was not specified for machinery use, a medium soil category was applied by default. CFP does not differentiate emission factors by soil type for machinery operations, so this assumption does not influence final emission results.

Overall, these targeted standardization steps were applied conservatively and only where necessary, prioritizing internal consistency and methodological transparency while acknowledging the inherent limitations of farm-level primary data collection across diverse systems.

3.9.6.   FORMATTING THE DATA FOR CFP

Once cleaned and validated, the final datasets were processed in a structured Excel-based preprocessing environment, which served as the central workspace for quality control, variable harmonization, unit standardization, and application of documented assumptions. Following this step, the curated Excel datasets were programmatically converted using Python scripts into JSON files structured in full alignment with the CFP application programming interface (API) endpoint specifications. This included mapping each variable to the required CFP schema, ensuring correct data types, field naming conventions, and hierarchical structure consistent with the API requirements.

3.9.7.   RUNNING THE DATA IN CFP

The generated JSON files were then submitted to the CFP system using the POST/assessment/calculate endpoint to execute the model runs. This automated approach improved computational efficiency, ensured consistent application of modeling assumptions, and minimized the risk of manual data-handling errors.

Model execution generated detailed farm-level assessment outputs in JSON format. These outputs were subsequently parsed and exported into Excel, where results from all individual farm assessments were consolidated into a unified analytical dataset.

This consolidated dataset formed the basis for all downstream aggregation, statistical analysis, and reporting.

All preprocessing steps, data transformations, schema conversions, API interactions, and result extractions were fully documented, ensuring complete traceability from the original farm-level survey responses through to the final model outputs.

4. RESULTS

4.1. CARBON FOOTPRINT RESULTS

This section presents the carbon footprint results for coffee production across the five study countries, covering both Arabica and Robusta systems in Brazil, and Arabica systems in Colombia, Honduras, Mexico, and Peru.

4.1.1. FINAL RESULTS OVERVIEW

A high-level comparison across Brazil, Colombia, Honduras, Mexico, and Peru shows substantial variation in emission intensities. Table 7 summarizes the aggregated CFP baseline results for each country, expressed in kg CO_2-eq per kg of green bean equivalent (GBE).

COUNTRY	BASELINE RESULTS FROM CFP (kg CO_2-eq per kg GBE)
BRAZIL (ARABICA)	3.22
BRAZIL (ROBUSTA)	2.51
COLOMBIA	5.59
HONDURAS	4.87
MEXICO	1.46
PERU	2.84

Table 7: Results from CFP

As mentioned, the system boundaries for all country-level analyses were defined at the farm-gate level. This scope includes primary cultivation activities, farm-level processing (where applicable), upstream transport of inputs to the farm—such as fertilizers, pesticides, fuel, and other production materials from suppliers or distributors—and downstream transportation of harvested coffee products (e.g., cherries or parchment or green beans, where applicable) from the farm to the first point of aggregation or processing beyond the farm gate. It is important to note that the transportation activities within the farm (e.g., moving of product from one end of the farm to the other end) were excluded from the system boundary, as reliable and

consistent farm-level data for these operations are generally not available and, based on discussions among Consortium and Supplier Partners (during the USAID GIA study and the current project), were assessed to have a negligible influence on final emission results.

Furthermore, regional-level baseline results were not reported, as the number of farms available at the regional scale was insufficient to achieve adequate statistical power, meaning that the sample sizes were too small to reliably estimate regional means, variability, or confidence intervals in a way that would be representative of regional production circumstances.

Table 8 showcases a further categorical breakdown of the results. The results indicate that emissions are primarily driven by fertilizer production and use, crop residue, machinery operations, and/or wastewater management. These drivers vary across countries due to differences in input intensity, residue treatment practices, and productivity levels, which affect emissions per functional unit (kg CO_2-eq per kg GBE). Processing arrangements also differ between origins; some farms process coffee on-site, while others deliver cherries to off-farm facilities, introducing additional heterogeneity that is nevertheless representative of national production contexts.

SOURCE	BRAZIL ARABICA	BRAZIL ROBUSTA	COLOMBIA	HONDURAS	MEXICO	PERU
Fertilizer use (production and application)	1.9	1.53	3.35	2.33	0.69	0.51
Crop residues	1.09	0.69	1.82	2.00	0.58	1.89
Machinery operations	0.09	0.08	0.30	0.25	0.12	0.28
Transport	0.07	0.05	0.01	0.02	0.02	0.04
Fuel & energy	0.03	0.05	0.07	0.03	0.02	0.02
Wastewater	0.02	0.001	0.04	0.21	0.02	0.11
Irrigation	0.002	0.10	0	0	0	0
Pesticides	0.001	0.004	0.001	0.008	0.0003	0.0008
Non-crop biomass estimates	-1.47	-0.14	-0.34	-0.187	-0.07	-0.184

Table 8: Emission breakdown per country (kg CO_2-eq per kg GBE)

Table 7 and Table 8 above summarize the core findings of the CFP assessments and offer complementary perspectives on national coffee production and related emissions. Table 9 (below) supplements these data with yield metrics, reporting both average and median coffee yields by country to aid interpretation of emission intensities across production systems. The modeling framework used in the study

averages GHG aggregation for the participating farms; however, the median values illustrated in Table 9 highlight the influence of extreme yields on national means.

It is important to contextualize that the values in Table 7 and Table 8 represent a snapshot of emissions for the specific assessment year, reflecting production conditions and management practices at that time. Although such annualized results are suitable for GHG accounting and reporting, they do not capture interannual variability in yields, inputs, or climate. To strengthen climate action planning and GHG inventories, an improved, sector-wide approach to collecting comparable data over multiple consecutive years should be developed to capture variability and long-term trends.

The study's annualized approach, however, is in line with the GHGP Corporate Accounting and Reporting Standard and the Corporate Value Chain (Scope 3) Standard principles, which state that inventories must reflect conditions within the defined reporting period; multi-year averaging would extend beyond the recommended temporal boundary. Thus, this study adopts a strict annual assessment approach, while recommending improved multi-year assessments rather than cross-year averaging as the preferred method for developing realistic, consistent, and policy-relevant national GHG inventories over time. Further limitations to this approach, along with implications for result interpretation and recommendations for future assessments, are discussed in detail in Section 10 of this report.

COUNTRY	ASSESSMENT YEAR		PREVIOUS YEAR		MEAN YIELD (TWO YEAR) (KG/HA)
	Median yield (kg/ha)	Average yield (kg/ha)	Median yield (kg/ha)	Average yield (kg/ha)	
Brazil Arabica	1800	2162	1600	1858	2010
Brazil Robusta	3392	3160	2747	2882	3021
Colombia	1015	1285	1012	1322	1304
Honduras	1007	1681	882	1423	1552
Mexico	836	1006	700	891	949
Peru	934	1425	881	1013	1219

Table 9: Average and median yield per country

4.1.2. RESULTS AT THE COUNTRY LEVEL

After providing an aggregated overview of the results across all countries, a closer look at a country level is required to identify specific emission drivers. To interpret the country-level input parameters, analyze their variability, and determine their relative influence on GHG emissions, an additional statistical approach was employed: the Z-score method.

The Z-score statistical method was applied independently for each country across all emission categories (fertilizer use, crop residues, machinery operations, transport, fuel and energy, wastewater, irrigation, pesticides, and non-crop biomass estimates) as well as for the corresponding input parameters associated with these individual categories. The Z-score standardizes individual data points relative to the mean and the dispersion of the dataset, allowing for comparability across different parameters[13].

It is calculated using the following formula:

$$Z = \frac{x_i - \bar{x}}{\sigma}$$

where:
- x_i = individual value of the parameter,
- $\bar{x}$ = mean of the dataset,
- σ = standard deviation of the dataset.

The standard deviation (σ) is computed as:

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n - 1}}$$

where:

- n = total number of observations.

After calculating the Z-score for each input parameter and the corresponding emission values, the results were interpreted based on statistical thresholds given by this statistical methodology. These are the following thresholds and their interpretations[9]:
- $Z = 0$: value equals the mean,
- $Z = \pm 1$: one standard deviation above or below the mean,
- $|Z| > 2$: value is unusual and often considered an outlier,
- $|Z| > 3$: value is highly unusual and typically considered an outlier.

It is important to highlight that the Z-score approach was chosen because it accounts for both the central tendency and the dispersion of the dataset, making it a more robust measure than simple percentage deviations. This approach enables the identification of extreme deviations (outliers) in input parameters or emission values, which may indicate emission hotspots or anomalies in agricultural practices. Such

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[13] McLeod, S. (2023, October 6). Z-score: Definition, formula, calculation & interpretation. Simply Psychology. https://www.simplypsychology.org/z-score.html

hotspots are critical for understanding variability and targeting mitigation strategies within coffee supply chains, and they give a full picture of the supply chain[14].

The Z-score is also inherently unitless, which makes it particularly suitable for analyzing input parameters that differ in units across categories. For example, wastewater may be expressed in liters, while the yield will be measured in kgs or tons, but emissions are ultimately normalized to kgs of CO_2-eq per kg GBE. The Z-score's unitless property ensures comparability across diverse parameters and units without introducing bias from differing measurement scales. As the entire hotspot analysis of the main emissions and country-level assessments of the study is based on the functional unit kg CO_2-eq per kg GBE, ensuring methodological consistency in units of measure and other aspects is important, so that results can be interpreted correctly, and higher outliers in emissions can be identified. The subsequent sections present country-specific results analyzed by the Z-score method and provide contextual interpretation for high-emission drivers.

4.1.2.1. RESULTS FOR BRAZIL ARABICA

The average carbon footprint of the Brazilian Arabica coffee supply chain up to farm-gate is 3.22 kg CO_2-eq per kg GBE, corresponding to total emissions of 322,760,318 kg CO_2-eq. Z-score analysis of yield confirms the robustness of this estimate, with only 21 farms exhibiting values above the mean, indicating that the national average is not driven by extreme production systems.

This Brazilian footprint is primarily shaped by input-intensive agronomic practices rather than downstream or processing-related activities. Fertilizer use is the dominant emission source, contributing 1.90 kg CO_2-eq per kg GBE (59%), reflecting both relatively high application rates and the combined impact of upstream fertilizer production and direct soil emissions. Crop residue management is the second largest contributor, at 1.09 kg CO_2-eq per kg GBE (34%), driven largely by pruning and leaf litter decomposition. In Brazil, a majority of farms did not conduct pruning during the assessment year, but where pruning occurred, residues were predominantly left on the field, sustaining nitrous oxide (N_2O) emissions through nitrogen mineralization. Methane emissions (CH_4) arose mainly from burning and limited anaerobic residue handling, resulting in an even split between N_2O and CH_4 within the residue category.

Machinery operations contribute 0.09 kg CO_2-eq per kg GBE (3%), reflecting mechanisation levels that are higher than in most other origins in the study. In contrast, emissions from wastewater, transport, fuel and energy use, irrigation energy, and pesticides are all marginal, each contributing less than 3%. This reflects limited on-farm wet processing, centralised aggregation structures, and relatively efficient

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[14] Z-score. (2008). In W. Kirch (Ed.), Encyclopedia of public health (p. 1484). Springer. https://doi.org/10.1007/978-1-4020-5614-7_3826

logistics. Overall, Brazil's Arabica footprint up to farm-gate is characterised by high production efficiency but elevated input intensity, making fertilizer and residue management the primary mitigation levers.

Emissions breakdown – Brazil Arabica	CATEGORY	KG CO_2-EQ PER KG GBE	PERCENTAGE OF CONTRIBUTION
	Fertilizer use	1.9	59%
	Crop residues	1.09	34%
	Machinery operations	0.09	3%
	Transport	0.07	2%
	Fuel & energy	0.03	0.9%
	Wastewater	0.02	0.6%
	Irrigation	0.002	0.06%
	Pesticides	0.001	0.03%

Table 10: Emissions breakdown – Brazil Arabica

4.1.2.2. RESULTS FOR BRAZIL ROBUSTA

The average carbon footprint of the Brazilian Robusta coffee supply chain up to farm-gate is 2.51 kg CO_2-eq per kg GBE, corresponding to total emissions of 123,435,739.8 kg CO_2-eq. Z-score analysis of yield confirms the robustness of this estimate, with no farms exhibiting values above the mean.

The Brazilian Robusta footprint is primarily driven by fertilizer use, which is the dominant emission source, contributing 1.53 kg CO_2-eq per kg GBE, equivalent to approximately 61% of total emissions. This reflects both relatively high fertilizer application rates and the combined effect of upstream fertilizer manufacturing emissions and direct soil emissions (primarily N_2O). Crop residue management is the second largest contributor, accounting for 0.69 kg CO_2-eq per kg GBE (27%), driven mainly by pruning residues and leaf litter decomposition left on the field, which sustain N_2O emissions through nitrogen mineralization processes.

All remaining emission sources play a secondary role. Machinery operations contribute 0.08 kg CO_2-eq per kg GBE (3%), reflecting moderate mechanisation levels typical of Brazilian Robusta systems. Transport and fuel and energy use each contribute around 0.05 kg CO_2-eq per kg GBE (2%). Irrigation contributes 0.10 kg CO_2-eq per kg GBE (4%), highlighting the predominance of pumped irrigation in some production systems. Emissions from pesticides (0.004 kg CO_2-eq per kg GBE) and wastewater (0.001 kg CO_2-eq per kg GBE) are negligible, consistent with limited on-farm wet processing. Overall, the Brazilian Robusta carbon footprint up to farm-gate is characterized by high production efficiency combined with high mineral fertilizer contribution, followed by residue management and irrigation, together representing more than 90% of the emissions.

Emissions breakdown – Brazil Robusta	CATEGORY	KG CO$_2$-EQ PER KG GBE	PERCENTAGE OF CONTRIBUTION
	Fertilizer use	1.53	61%
	Crop residues	0.69	27%
	Machinery operations	0.08	3%
	Transport	0.05	2%
	Fuel & energy	0.05	2%
	Wastewater	0.001	0.03%
	Irrigation	0.10	4%
	Pesticides	0.004	0.15%

Table 11: Emissions breakdown – Brazil Robusta

4.1.2.3. RESULTS FOR COLOMBIA

The average carbon footprint of the Colombian Arabica coffee supply chain up to farm-gate is 5.59 kg CO$_2$-eq per kg GBE, with total emissions of 27,984,678 kg CO$_2$-eq. Yield-based Z-score analysis confirms the representativeness of this estimate, with only 13 out of 600 farms (2%) exceeding the mean.

Colombia's footprint is strongly dominated by fertilizer use, which contributes 3.35 kg CO$_2$-eq per kg GBE (60%). This reflects widespread reliance on mineral fertilizers with relatively high nitrogen content, resulting in substantial on-field N$_2$O emissions. Crop residue management is the second most significant source, contributing 1.82 kg CO$_2$-eq per kg GBE (33%). Residue emissions are primarily driven by field-based decomposition of pruning residues, leaf litter, and pulp, leading to a strongly N$_2$O-dominated emission profile, with CH$_4$ emissions arising mainly from heaps and pits used for processing residues.

Wastewater management represents the third most relevant category but remains minor at 0.04 kg CO$_2$-eq per kg GBE (0.7%), reflecting the limited number of farms performing on-farm wet processing. Transport, machinery, fuel and energy use, irrigation energy, and pesticide application together contribute only a small fraction of total emissions. Overall, Colombia's footprint up to farm-gate is characterized by high fertilizer intensity combined with structurally embedded residue emissions, while downstream and operational emissions remain comparatively insignificant.

	CATEGORY	KG CO$_2$-EQ PER KG GBE	PERCENTAGE OF CONTRIBUTION
	Fertilizer use	3.35	60%
	Crop residues	1.82	32%

Emissions breakdown – Colombia			
	Machinery operations	0.3	5%
	Transport	0.01	0.2%
	Fuel & energy	0.07	1.3%
	Wastewater	0.04	0.8%
	Irrigation	0.0	0%
	Pesticides	0.005	0.1%

Table 12: Emissions breakdown – Colombia

4.1.2.4. RESULTS FOR HONDURAS

The average carbon footprint of the Honduran Arabica coffee supply chain up to farm-gate is 4.87 kg CO_2-eq per kg GBE, corresponding to total emissions of 24,287,943 kg CO_2-eq. Yield-based Z-score analysis confirms the representativeness of this estimate, with only 15 out of 601 farms (2%) exceeding the mean. Honduras stands out for its balance between fertilizer and residue emissions, both of which play nearly equal roles in shaping the footprint.

Fertilizer use is still the largest contributor at 2.34 kg CO_2-eq per kg GBE (48%), driven by both upstream production emissions and direct soil emissions. Crop residue management follows closely at 2.00 kg CO_2-eq per kg GBE (41%), but unlike Brazil and Colombia, residue emissions in Honduras are characterized by a much higher share of CH_4. This reflects widespread anaerobic handling of pulp, husk, and leaf litter in heaps and pits, as well as continued use of burning for pruning residues.

Machinery operations contribute 0.25 kg CO_2-eq per kg GBE (5%), while wastewater emissions are notably higher (when compared to Brazil and Colombia) due to a larger share of farms conducting on-farm wet processing. Transport, fuel, and energy use, irrigation energy, and pesticides each remain below 5%, but collectively contribute more than in most other origins. Overall, Honduras' footprint up to farm-gate reflects a structural reliance on anaerobic residue and wastewater management, making CH_4-focused interventions particularly relevant.

Emissions breakdown – Honduras	CATEGORY	KG CO₂-EQ PER KG GBE	% OF CONTRIBUTION
	Fertilizer use	2.34	48%
	Crop residues	2.00	41%
	Machinery operations	0.24	5%
	Transport	0.02	0.5%

Fuel & energy	0.027	0.6%
Wastewater	0.21	4.4%
Irrigation	0.0	0%
Pesticides	0.008	0.18%

Table 13: Emissions breakdown – Honduras

4.1.2.5. RESULTS FOR MEXICO

The average carbon footprint of the Mexican Arabica coffee supply chain up to farm-gate is 1.46 kg CO_2-eq per kg GBE, with total emissions of 6,407,002 kg CO_2-eq, making Mexico the lowest-intensity origin assessed in this study. Although the Z-score analysis of yield indicates greater variability than in the other countries, as 41 farms out of 605 are above the mean (6,8%), the relative share remains limited, supporting the conclusion that the dataset remains robust and representative at national level.

Fertilizer use remains the dominant source at 0.70 kg CO_2-eq per kg GBE (48%), although absolute application rates are lower than in other countries. Crop residue management contributes 0.58 kg CO_2-eq per kg GBE (40%), reflecting a mixed management system where residues are both left on the field and managed in heaps or pits. This results in a residue emission profile dominated by N_2O but with a non-negligible methane CH_4 component.

Machinery operations account for 0.12 kg CO_2-eq per kg GBE (8%), while wastewater emissions are more visible (again when compared to Brazil and Colombia) due to a higher prevalence of on-farm processing. Transport emissions are influenced by long downstream distances for a small number of farms, but remain minor at an overall supply-chain level. In sum, Mexico's footprint up to farm-gate reflects lower input intensity and moderate yields, with mitigation opportunities centered on reducing anaerobic residue and wastewater handling rather than fertilizer reduction alone.

Emissions breakdown – Mexico	CATEGORY	KG CO₂-EQ PER KG GBE	% OF CONTRIBUTION
	Fertilizer use	0.69	48%
	Crop residues	0.58	40%
	Machinery operations	0.12	8%
	Transport	0.02	1%
	Fuel & energy	0.02	1.4%
	Wastewater	0.024	1.7%
	Irrigation	0	0%
	Pesticides	0.0003	0.02%

Table 14: Emissions breakdown – Mexico

4.1.2.6. RESULTS FOR PERU

The average carbon footprint of the Peruvian Arabica coffee supply chain up to farm-gate is 2.84 kg CO_2-eq per kg GBE, with total emissions of 6,930,818 kg CO_2-eq. Z-score analysis confirms a highly representative dataset, with only 15 out of 620 farms (2%) exceeding the mean yield.

Peru is unique among the assessed origins in that crop residue management rather than fertilizer overwhelmingly dominates the footprint, contributing 1.89 kg CO_2-eq per kg GBE (67%). This reflects high residue volumes combined with consistent residue generation across farms. Fertilizer use contributes 0.51 kg CO_2-eq per kg GBE (18%), substantially lower than in the other origins, while machinery operations account for 0.28 kg CO_2-eq per kg GBE (10%), reflecting relatively labor-intensive but mechanized post-harvest operations.

Unlike Honduras, Peru shows widespread adoption of aerobic composting for processing residues, which limits CH_4 emissions despite the large residue share. As a result, residue emissions are dominated by N_2O rather than CH_4. Wastewater emissions are more visible (when compared to Brazil, Colombia, and Mexico) due to on farm processing, but remain secondary compared to residues. Overall, Peru's footprint up to farm-gate is shaped by biomass-driven emission processes rather than input intensity, positioning residue management as the central mitigation lever.

Emissions breakdown – Peru	CATEGORY	KG CO_2-EQ PER KG GBE	% OF CONTRIBUTION
	Fertilizer use	0.51	18%
	Crop residues	1.89	67%
	Machinery operations	0.28	10%
	Transport	0.04	1%
	Fuel & energy	0.02	1%
	Wastewater	0.11	4%
	Irrigation	0	0%
	Pesticides	0.001	0%

Table 15: Emissions breakdown – Peru

5. ANALYSES PER EMISSION SOURCE

5.1. FERTILIZER PRODUCTION AND APPLICATION

5.1.1. OVERVIEW

Fertilizer use (production and application) is widely recognized as a major contributor to GHG emissions in agricultural systems and are consistently identified as a dominant source of emissions in coffee production at the farm level. Numerous LCA studies have shown that mineral fertilizers, particularly nitrogen-based products, account for a substantial share of total farm-level emissions due to (1) a combination of upstream emissions from industrial manufacturing and (2) downstream emissions released after application to soils (Noponen et al., 2012[15]; Hergoualc'h et al., 2012[16]; Poore & Nemecek, 2018[17]). This dominance is further amplified by the fact that the principal GHG released from fertilized soils is N_2O, which has a global warming potential approximately 273 times higher than CO_2 over a 100-year time horizon, meaning that even relatively small quantities of N_2O emissions translate into substantial CO_2-eq impacts.

Upstream emissions associated with fertilizer production arise primarily from energy-intensive industrial processes, most notably the synthesis of nitrogen fertilizers via the Haber-Bosch process, which relies heavily on fossil fuels and generates significant CO_2 emissions (Brentrup et al., 2016[18]; IPCC, 2019[19]. These emissions vary substantially depending on the type of fertilizer produced, the efficiency of production technologies, and the regional energy mix used during manufacturing. As a result, emission factors for fertilizer production differ across countries and regions, introducing an inherent source of uncertainty when the precise origin of fertilizers is unknown or when

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[15] Noponen, M. R. A., Edwards-Jones, G., Haggar, J. P., Soto, G., Attarzadeh, N., & Healey, J. R. (2012). Greenhouse gas emissions in coffee production systems: Case studies from Central America. Journal of Cleaner Production, 44, 1–10. https://doi.org/10.1016/j.jclepro.2012.11.042

[16] Hergoualc'h, K., Blanchart, E., Skiba, U., Hénault, C., & Harmand, J.-M. (2012). Greenhouse gas emissions from coffee systems: A review of field measurements and modeling. Agriculture, Ecosystems & Environment, 152, 83–94. https://doi.org/10.1016/j.agee.2012.02.014

[17] Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science, 360(6392), 987–992. https://doi.org/10.1126/science.aaq0216

[18] Brentrup, F., Hoxha, A., & Christensen, B. (2016, October). Carbon footprint analysis of mineral fertilizer production in Europe and other world regions. In Proceedings of the 10th International Conference on Life Cycle Assessment of Food (LCA Food 2016) (pp. 482–490). University College Dublin; Fertilizers Europe. https://www.researchgate.net/publication/312553933_Carbon_footprint_analysis_of_mineral_fertilizer_production_in_Europe_and_other_world_regions

[19] Intergovernmental Panel on Climate Change. (2019). 2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories. Institute for Global Environmental Strategies. https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/

compound fertilizers (e.g., NPK blends) are assembled in one location using nitrogen components produced elsewhere.

Fertilizer-related GHG emissions in coffee production systems are quantified using a life-cycle-based methodology aligned with the IPCC 2006 Guidelines, the 2019 IPCC Refinement, the GHGP Land Sector and Removals Guidance, and ISO 14040/14044 principles. The CFP tool accounts for upstream emissions from fertilizer production and transport using fertilizer-specific life-cycle emission factors derived from various databases and peer-reviewed industry sources, covering raw material extraction, manufacturing, and packaging. Direct soil N_2O emissions resulting from nitrogen application are estimated using the IPCC Tier 1 approach, based on total nitrogen inputs from mineral and organic fertilizers. In addition, indirect N_2O emissions from nitrogen losses via ammonia and nitrate leaching are quantified using IPCC default fractions and emission factors. Together, these components provide a comprehensive cradle-to-farm-gate accounting of fertilizer emissions.

Given the significance of fertilizers in the overall GHG balance, this study paid careful attention to capturing fertilizer-related data in a consistent and transparent manner across countries. Fertilizer-related assessments explicitly included both emissions from fertilizer manufacturing and indirect soil emissions following application, in line with the methodological requirements of the CFP. While uncertainties related to fertilizer origin and composition cannot be eliminated, the use of standardized emission factors and systematic data quality checks ensure that fertilizer-related emissions are robustly representative and comparable across national supply chains. It should be noted that the results presented below are based on fertilizer application rates as reported by farmers, and that actual fertilizer use could not be independently verified through soil analysis.
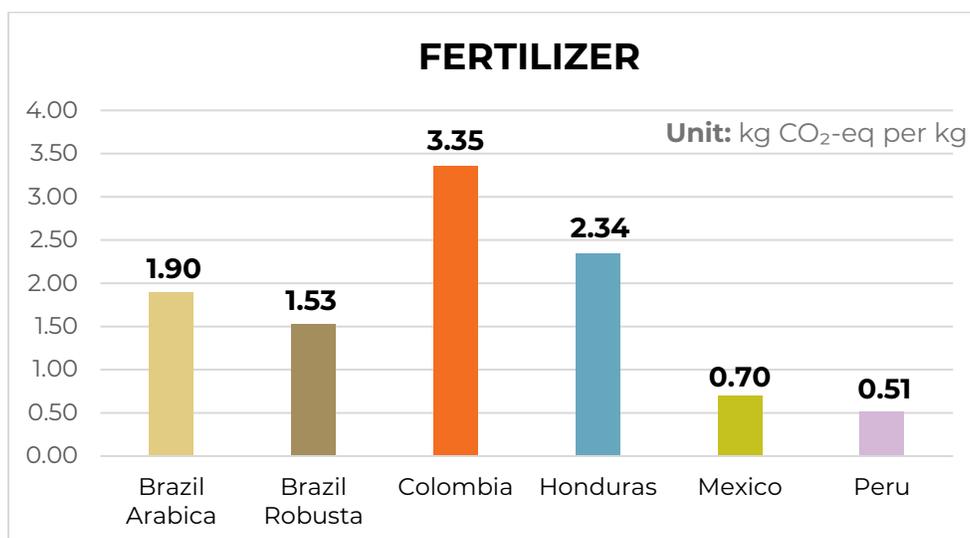
Figure 6: Breakdown of fertilizer emissions by countries

5.1.2. RESULTS FOR BRAZIL ARABICA

Fertilizer use (production and application) was the most significant source of GHG emissions in the Brazilian Arabica coffee supply chain up to farm-gate. Fertilizer-related emissions amounted to 1.90 kg CO_2-eq per kg GBE, representing a substantial share of the total farm-gate baseline. When expressed per unit of land area, fertilizer emissions reached 4,424 kg CO_2-eq per ha.

Fertilizer application rates in Brazil (Arabica) were higher than in the other Latin American countries included in this study, with an average use of 2,708 kg per ha. On a quantity-applied basis, synthetic fertilizers accounted for 71% of total fertilizer inputs, while organic fertilizers represented the remaining 29%. This widespread and intensive use of mineral fertilizers largely explains the prominence of fertilizer-related emissions in the Brazilian Arabica results. Of the total fertilizer-related emissions, approximately 46% are attributable to upstream fertilizer production and transport, while around 54% arise from on-field application, primarily driven by direct and indirect soil N_2O emissions. In absolute terms, this corresponds to approximately 1,769.69 kg CO_2-eq per ha from fertilizer production and 2,654.88 kg CO_2-eq per ha from on-field application, confirming that field-level nitrogen management is the dominant driver of fertilizer-related emissions in the Brazilian Arabica coffee supply chain.

Fertilizer type applied
Brazil Arabica

29 %
71 %

■ Synthetic   ■ Organic

Figure 7: Fertilizer type applied – Brazil Arabica

Fertilizer breakdown	kg CO_2-eq per kg GBE
Production	0.87
Application	1.03
Total	**1.90**

Table 16: Fertilizer breakdown – Brazil Arabica

Further Z-score analysis indicates the presence of a limited number of farms with comparatively high fertilizer-related emissions, reflecting a small proportion of producers applying substantially higher fertilizer inputs. When fertilizer emissions are expressed per kg GBE, 22 farms exhibit Z-scores more than 2, corresponding to approximately 4% of the assessed farms. These higher-input systems should be explicitly considered when defining mitigation strategies, given fertilizer application's direct influence on the overall carbon footprint. However, due to their limited number, these farms do not materially distort the aggregate emission results. Overall, the dataset provides a robust and representative picture of the Brazilian Arabica supply chain, while appropriately capturing underlying heterogeneity in fertilizer management practices.

5.1.3. RESULTS FOR BRAZIL ROBUSTA

Fertilizer use (production and application) was the most significant source of GHG emissions in the Brazilian Robusta coffee supply chain up to farm-gate. Fertilizer-related emissions amounted to 1.53 kg CO_2-eq per kg GBE, representing approximately 61% of the total farm-gate carbon footprint. When expressed per unit of land area, fertilizer emissions reached 4,848.5 kg CO_2-eq per ha, confirming the central role of nutrient management in shaping overall emission intensities.

Fertilizer application rates in Brazilian Robusta systems were comparatively high, with an average use of 2,766 kg per ha. On a quantity-applied basis, synthetic fertilizers accounted for 98% of total fertilizer inputs, while organic fertilizers represented the remaining 2%. This strong reliance on synthetic fertilizers largely explains the prominence of fertilizer-related emissions in the Brazilian Robusta results. Of the total fertilizer-related emissions, approximately 42% are attributable to upstream fertilizer production and transport, while 58% arise from on-field application, primarily driven by direct and indirect soil N_2O emissions. This split highlights that field-level nitrogen management is the dominant driver of fertilizer-related emissions in the Robusta production system.

Fertilizer breakdown	kg CO_2-eq per kg GBE
Production	0.64
Application	0.89
Total	**1.53**

Table 17: Fertilizer breakdown – Brazil Robusta

Z-score analysis further illustrates heterogeneity in fertilizer management practices without materially affecting aggregate results. When fertilizer emissions are analyzed on a per-ha basis, 14 farms exhibit values above the mean, while 16 farms show Z-scores greater than 2, indicating a limited number of higher-emission systems. Analysis of fertilizer application rates (kg per ha) identifies four farms with Z-scores exceeding 4, reflecting exceptionally high input use. Sensitivity analysis indicates that excluding these high-input farms would alter the national average carbon footprint by only 0.12%, demonstrating that their influence on the final results is negligible. Overall, the dataset provides a robust and representative picture of fertilizer-related emissions in Brazilian Robusta production, while appropriately capturing underlying variability in input intensity.

Fertilizer type applied
Brazil Robusta

2 %

98 %

■ Synthetic   ■ Organic
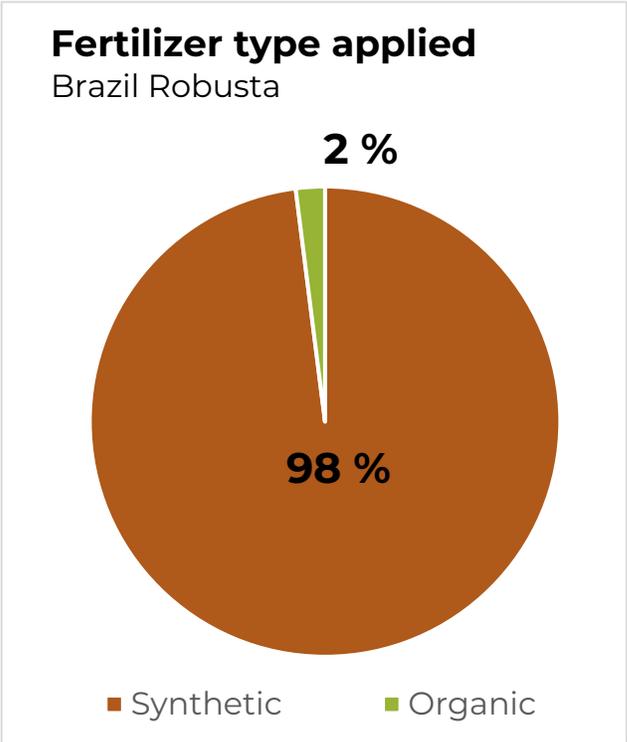
Figure 8: Fertilizer type applied – Brazil Robusta

5.1.4. RESULTS FOR COLOMBIA

Fertilizer use (production and application) was the most significant source of GHG emissions in the Colombian coffee supply chain up to farm-gate. Fertilizer-related emissions amounted to 3.35 kg CO_2-eq per kg GBE, representing a substantial share of the national farm-gate baseline. On a quantity-applied basis, synthetic fertilizers accounted for 96% of total fertilizer inputs, while organic fertilizers represented the remaining 4%.

The widespread use of synthetic fertilizers in Colombia, including both standard formulations and company-specific NPK blends, is associated with higher nitrogen application rates and consequently higher emission intensities, explaining the prominence of fertilizer-related emissions in the Colombian results.

Of the total fertilizer-related emissions, approximately 43% are attributable to upstream fertilizer production and transport, while around 57% arise from on-field application, primarily driven by direct and indirect soil N_2O emissions. In absolute terms, this corresponds to approximately 2,046.66 kg CO_2-eq per ha from fertilizer production and 2,713.01 kg CO_2-eq per ha from on-field application, confirming that field-level nitrogen management is the dominant driver of fertilizer-related emissions in the Colombian coffee supply chain.

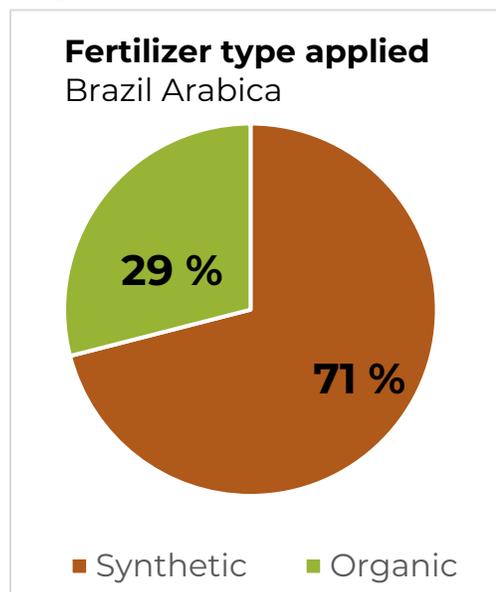**Fertilizer type applied**
Colombia

Figure 9: Fertilizer type applied – Colombia

Fertilizer breakdown	kg CO_2-eq per kg GBE
Production	1.45
Application	1.90
Total	**3.35**

Table 18: Fertilizer breakdown – Colombia

Further Z-score analysis indicates that the observed results are not driven by a small number of extreme values. When fertilizer emissions are expressed per unit of output (kg CO_2-eq per kg GBE), only 7 out of 600 farms exceed the mean, representing 1.2% of the sample. When emissions are evaluated per ha, 24 farms are classified as outliers, corresponding to approximately 4% of the dataset. In both cases, the proportion of outliers remains statistically minor, indicating that fertilizer-related emissions are relatively consistent across farms. Overall, the dataset provides a robust and representative picture of the Colombian Arabica supply chain, while appropriately capturing underlying heterogeneity in fertilizer management practices.

Fertilizer type applied Honduras

- Synthetic
- Organic
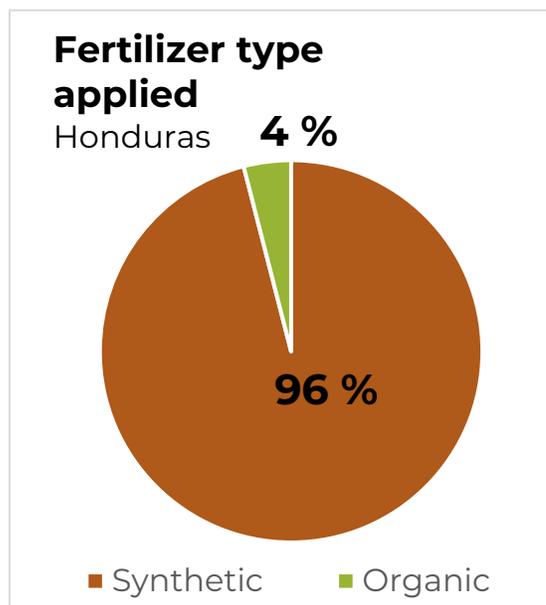
Figure 10: Fertilizer type applied – Honduras

5.1.5. RESULTS FOR HONDURAS

Fertilizer use (production and application) was one of the most significant sources of GHG emissions in the Honduran coffee supply chain up to farm-gate. Fertilizer-related emissions amounted to 2.34 kg CO_2-eq per kg GBE, corresponding to 3,623 kg CO_2-eq per ha.

Fertilizer application is a routine component of farm management in Honduras, with farms commonly applying standard mineral formulations as well as NPK blends. On a quantity-applied basis, synthetic fertilizers accounted for 96% of total fertilizer inputs, while organic fertilizers represented the remaining 4%. This widespread and regular use of mineral fertilizers explains the prominent contribution of fertilizer use to the overall carbon footprint of Honduran coffee production up to farm-gate.

Of the total fertilizer-related emissions, approximately 42% are attributable to upstream fertilizer production and transport, while around 58% arise from on-field application, primarily driven by direct and indirect soil N_2O emissions. In absolute terms, this corresponds to approximately 1,413.17 kg CO_2-eq per ha from fertilizer production and 2210.35 kg CO_2-eq per ha from on-field application, confirming that field-level nitrogen management is the dominant driver of fertilizer-related emissions in the Honduran coffee supply chain.

Fertilizer breakdown	kg CO_2-eq per kg GBE
Production	0.99
Application	1.35
Total	**2.34**

Table 19: Fertilizer breakdown – Honduras

Further Z-score analysis indicates a high degree of consistency across farms. When fertilizer emissions are expressed per unit of output (kg CO_2-eq per kg GBE), 18 farms exhibit Z-scores greater than 1, representing approximately 3% of the sample. A similar pattern is observed when emissions are expressed per ha, with 21 farms classified as outliers, corresponding to around 3.5% of the dataset. In both cases, the proportion of outliers remains statistically minor and does not compromise the representativeness of the farm-gate baseline for fertilizer emissions in Honduras.

5.1.6. RESULTS FOR MEXICO

Fertilizer use (production and application) was the most significant source of GHG emissions in the Mexican coffee supply chain up to farm-gate. Fertilizer-related emissions amounted to 0.70 kg CO_2-eq per kg GBE, corresponding to 1,995 kg CO_2-eq per ha. Compared to other countries in the study, fertilizer application rates in Mexico were substantially lower, with an average application rate of 751 kg per ha.

On a quantity-applied basis, synthetic fertilizers accounted for 99% of total fertilizer inputs, while organic fertilizers represented the remaining 1%. Despite the lower absolute application rates, this widespread reliance on synthetic inputs explains why fertilizer use still emerges as the dominant emissions source in the Mexican results.

Of the total fertilizer-related emissions, approximately 39% are attributable to upstream fertilizer production and transport, while around 61% arise from on-field application, primarily driven by direct and indirect soil N_2O emissions. In absolute terms, this corresponds to approximately 817.95 kg CO_2-eq per ha from fertilizer production and 1,177.06 kg CO_2-eq per ha from on-field application, confirming that field-level nitrogen management is the dominant driver of fertilizer-related emissions in the Mexican coffee supply chain.

Fertilizer type applied
Mexico

1 %

99 %

■ Synthetic   ■ Organic
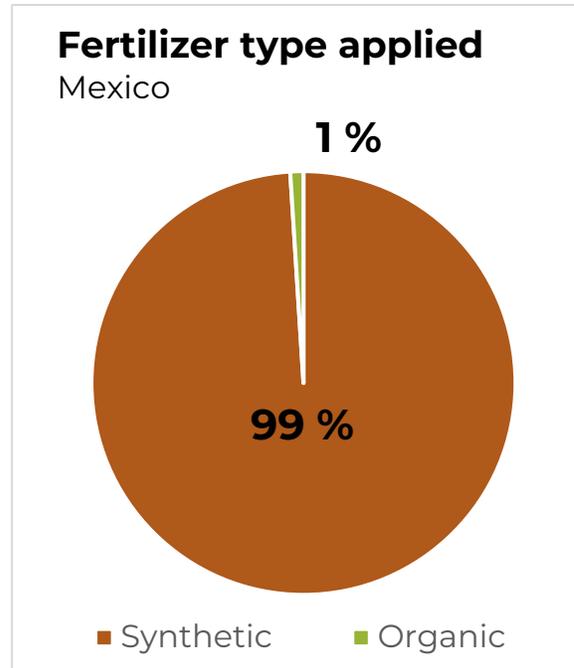
Figure 11: Fertilizer type applied – Mexico

Fertilizer breakdown	kg CO_2-eq per kg GBE
Production	0.28
Application	0.42
Total	**0.70**

Table 20: Fertilizer breakdown – Mexico

Further Z-score analysis indicates the presence of a limited number of higher-emitting farms. When fertilizer emissions are expressed per unit of output (kg CO_2-eq per kg GBE), 39 farms exhibit elevated Z-scores, representing approximately 6.4% of the sample. Although slightly higher than in some other countries, this proportion remains small and indicates that fertilizer emissions are not driven by extreme values alone. Overall, the dataset provides a robust and representative picture of the Mexican coffee supply chain, while appropriately capturing underlying heterogeneity in fertilizer management practices.

5.1.7. RESULTS FOR PERU

Fertilizer use (production and application) was the second most significant source of GHG emissions in the Peruvian coffee supply chain up to farm-gate. Fertilizer-related emissions amounted to 0.51 kg CO_2-eq per kg GBE, representing a comparatively small contribution to the national farm-gate baseline (28%) relative to other origins assessed in this study.

Fertilizer application in Peru appeared generally limited, and where applied, typically consisted of standard mineral formulations rather than customized NPK blends. This relatively low input intensity is a key factor explaining the comparatively small contribution of fertilizer use to total emissions. On a quantity-applied basis, synthetic fertilizers accounted for 60% of total fertilizer inputs, while organic fertilizers represented the remaining 40%.

Of the total fertilizer-related emissions, approximately 50% are attributable to upstream fertilizer production and transport, while around 50% arise from on-field application, primarily driven by direct and indirect soil N_2O emissions. In absolute terms, this corresponds to approximately 326.47 kg CO_2-eq per ha from fertilizer production and 399.02 kg CO_2-eq per ha from on-field application, confirming that field-level nitrogen management remains the dominant driver of fertilizer-related emissions in the Peruvian coffee supply chain.
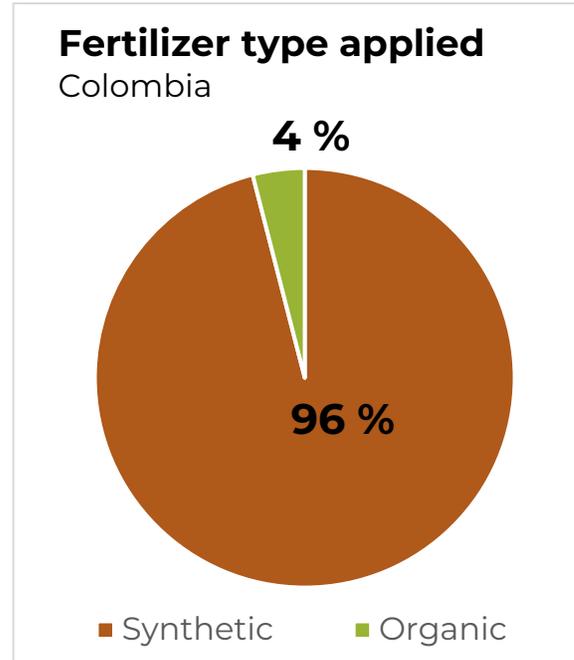
Fertilizer type applied
Peru
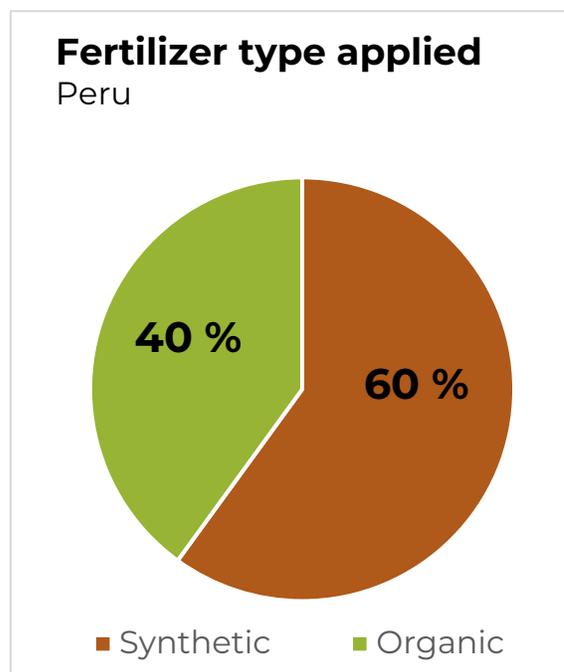
Figure 12: Fertilizer type applied – Peru

Fertilizer breakdown	kg CO₂-eq per kg GBE
Production	0.25
Application	0.26
Total	**0.51**

Table 21: Fertilizer breakdown – Peru

Further Z-score analysis confirms the stability of these results. When fertilizer emissions are expressed per unit of output (kg CO_2-eq per kg GBE), only 19 farms exceed the mean, representing approximately 3% of the sample. A similar pattern is observed when emissions are evaluated per ha, with 25 farms classified as outliers, corresponding to approximately 4% of the dataset. In both cases, the share of outliers remains statistically minor and does not compromise the representativeness of the farm-gate baseline for fertilizer-related emissions in Peru.

5.2. FUEL AND ENERGY USE

5.2.1. OVERVIEW

In CFP, GHG emissions from fuel and energy use are calculated using a direct activity-based approach consistent with IPCC guidance and GHGP. Emissions are estimated based on the actual quantities of fuel and electricity consumed for field and farm operations. Farmers report their consumption of energy carriers such as diesel, petrol, Liquified Petroleum Gas (LPG), natural gas, electricity, and biofuels, either in physical units (liters, kgs) or in energy units (kWh). CFP then applies fuel- and country-specific emission factors sourced primarily from internationally-recognized datasets, including the UK Department for Environment, Food & Rural Affairs (DEFRA), the UK Department for Energy Security and Net Zero (DESNZ), and the International Energy Agency (IEA). These factors account for both combustion emissions and upstream well-to-tank emissions, ensuring a full fuel life-cycle perspective.

For electricity, CFP uses national grid emission factors that reflect the country-specific power generation mix. Bioenergy sources (such as fuel wood, biogas, biodiesel, and bioethanol blends) are treated in line with GHGP and IPCC conventions. Biogenic CO_2 emissions from combustion are reported separately as out-of-scope, while any fossil fuel component in blended fuels is included in the main footprint. Embedded emissions from the production of renewable electricity (e.g. wind, solar, hydropower) are included on a cradle-to-gate basis.

The methodology ensures that fuel and energy emissions in CFP represent a transparent, consistent, and comparable estimate of on-farm energy use across countries and production systems and captures both direct combustion emissions and upstream supply chain emissions associated with agricultural energy consumption.
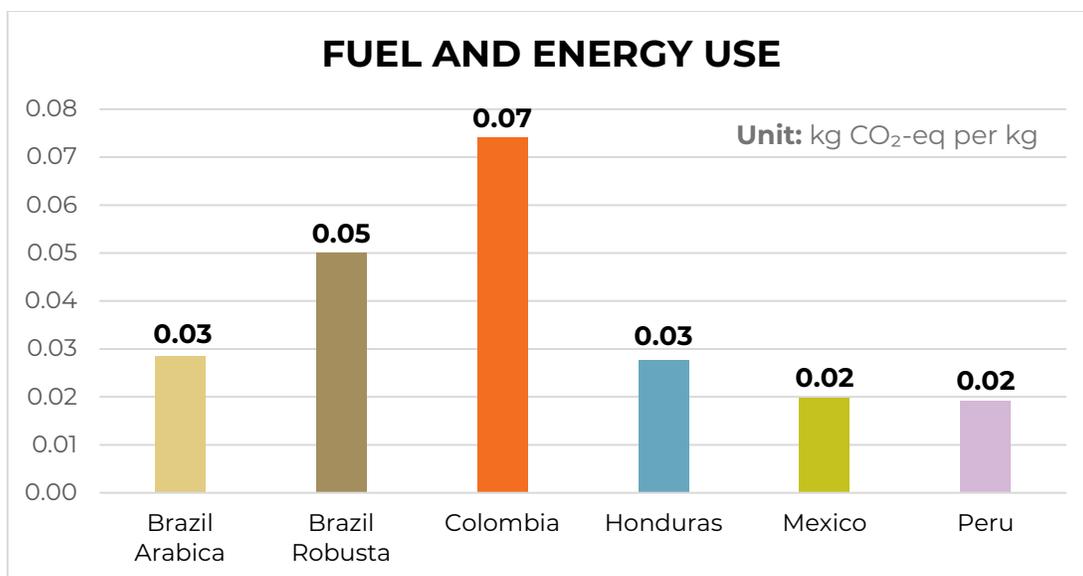
Figure 13: Breakdown of fuel and energy use by countries

5.2.2. RESULTS FOR BRAZIL ARABICA

Fuel and energy use represented only a minor source of GHG emissions in the Brazilian Arabica coffee supply chain up to farm-gate. According to the analysis, total emissions from this category amounted to 2,849,518.65 kg CO_2-eq, corresponding to 0.028 kg CO_2-eq per kg GBE and representing just 0.9% of total farm-gate emissions.

The Z-score analysis shows that 10 out of 500 farms have Z-scores greater than 1, with only 2 farms exhibiting exceptionally high values. As these farms account for just 0.4% of the sample, fuel and energy emissions remain insignificant in relation to total emissions up to farm-gate.

Overall, the use of biomass and fossil fuels for on-farm processing remained limited within the sample, with most emissions in this category driven by grid electricity. There were relatively few farms (21) that carried out processing activities, but their higher electricity demand resulted in a disproportionate contribution to total fuel and energy emissions within the category, driven by the high consumption of mineral diesel for processing operations.

5.2.3. RESULTS FOR BRAZIL ROBUSTA

Fuel and energy use represent a minor but non-negligible source of GHG emissions in the Brazilian Robusta coffee supply chain up to farm-gate. Total emissions from this category amount to 2,415,206 kg CO_2-eq, corresponding to 0.05 kg CO_2-eq per kg GBE and accounting for approximately 2% of total farm-gate emissions. This confirms that fuel and energy use play a secondary role in shaping the overall carbon footprint when compared with dominant sources such as fertilizers and crop residues.

Z-score analysis indicates that fuel and energy emissions are highly concentrated within a small subset of farms. When mineral diesel use is analysed, five farms exhibit Z-scores greater than 2, whereas no farms exceed this threshold for electricity consumption alone. However, when emissions are expressed per unit of output (kg CO_2-eq per kg GBE) and per unit of land area (kg CO_2-eq per ha), the same farms consistently show Z-scores greater than 2, indicating structurally higher energy intensity rather than artifacts of scaling. These farms are characterised by substantially higher diesel use and electricity consumption relative to the rest of the sample.

Sensitivity analysis shows that excluding these high-energy farms results in a 6.9% difference in fuel and energy related emissions. While this change is material for the fuel and energy category itself, the small share of these farms within the overall sample limits their influence on the total farm-gate carbon footprint. Instead, their presence highlights the underlying heterogeneity in energy use patterns within Brazilian Robusta production systems, likely linked to differences in on-farm processing activities. Overall, the results confirm that fuel and electricity use remain a secondary emission source at the national level, while pointing to targeted mitigation opportunities among a limited number of high-energy consumption farms.

5.2.4.   RESULTS FOR COLOMBIA

Fuel and energy use accounted for a minor share of GHG emissions in the Colombian coffee supply chain up to farm-gate. According to the analysis, fuel and energy-related emissions amounted to 349,384.31 kg CO_2-eq, corresponding to 0.07 kg CO_2-eq per kg GBE and representing only 1.32% of total farm-gate emissions. This indicates that energy use plays a limited role in the overall farm-gate carbon footprint of Colombian coffee production.

Further Z-score analysis confirms that these results are not driven by a small number of extreme values. Only 5 out of 600 farms exhibit fuel and energy emissions above the mean, corresponding to approximately 1% of the sample. Although these farms display comparatively high energy-related emissions, their limited number does not materially affect the aggregate results. Overall, fuel and energy emissions remain insignificant relative to total emissions across the Colombian coffee supply chain up to farm-gate.

A clear distinction is observed between processing and non-processing farms. Farms that conduct on-farm processing exhibit substantially higher fuel and energy-related emissions, reaching 45,274.82 kg CO_2-eq and accounting for 48.5% of emissions within this category. This is primarily driven by the intensive use of coal and fuel wood for processing activities. In contrast, fuel and energy emissions from non-processing farms remain marginal at the farm level, with biomass and fossil charcoal use contributing only 226 kg CO_2-eq.

5.2.5. RESULTS FOR HONDURAS

Fuel and energy use contributed only marginally to the overall carbon footprint in Honduras up to farm-gate. Emissions from this category amounted to 137,683.37 kg CO_2-eq, corresponding to 0.027 kg CO_2-eq per kg GBE and representing just 0.57% of total emissions.

The Z-score analysis indicates that 16 out of 601 farms had Z-scores greater than 1, with only 2 farms displaying exceptionally high values. As these farms represent only 0.3% of the sample, fuel and energy emissions can be considered insignificant in the context of supply chain emissions up to farm-gate.

For farms that carried out processing within the farm boundary, the impact of fuel and energy use was substantially higher. Although only 24% of farms in the sample undertake processing activities, they are responsible for 46,339.47 kg CO_2-eq, representing 43.6% of total emissions within this category. This highlights the disproportionate influence of processing farms on fuel- and energy-related emissions in Honduras, driven primarily by the high consumption of mineral diesel by a relatively small number of such operations.

5.2.6. RESULTS FOR MEXICO

Fuel and energy use had only a minor impact on the overall carbon footprint in the Mexican coffee supply chain up to farm-gate. These emissions amounted to 87,158.42 kg CO_2-eq, corresponding to 0.019 kg CO_2-eq per kg GBE and representing just 1.3% of total emissions.

The Z-score analysis shows that 3 out of 605 farms exhibit Z-scores greater than 1, indicating a highly representative sample. One of these farms displays an exceptionally high Z-score of 24.26; however, as this represents only 0.1% of the sample,

fuel and energy emissions remain insignificant relative to total emissions up to farm-gate.

At the farm level, the use of biomass and fossil fuels for energy activities was marginal, with emissions of 6,301.59 kg CO_2-eq, accounting for 5.5% of total emissions within this category. These emissions are primarily associated with the high consumption of mineral diesel for limited processing activities, confirming that fuel and energy use remains a minor contributor to the overall carbon footprint in Mexico.

5.2.7.   RESULTS FOR PERU

In the Peruvian coffee supply chain up to farm-gate, emissions from fuel and energy use also played a very minor role in the overall carbon footprint. These emissions amounted to 0.02 kg CO_2-eq per kg GBE, corresponding to just 0.70% of total emissions.

The Z-score analysis indicates that 25 farms out of 600 show values above the mean, representing 4.17% of the sample. This slightly higher proportion has no material influence on the overall results.

Biomass and fossil charcoal had only a marginal influence on emissions in this category, while liquid fuels represented the dominant energy source compared to electricity. Emissions nevertheless remained low overall, amounting to 19.35 kg CO_2-eq for non-processing farms and 551.69 kg CO_2-eq for processing farms, driven by the high consumption of mineral diesel for on-farm processing activities.

5.3. PESTICIDE AND HERBICIDE USE

5.3.1.   OVERVIEW

In CFP, pesticide-related GHG emissions are quantified using life-cycle emission factors sourced from the World Food LCA Database (WFLDB), following the methodology of Nemecek et al. (2019) and aligned with IPCC guidelines. Emissions are calculated based on the quantity of pesticide applied per ha, the share of active ingredients in the product, and crop-specific emission factors that represent the cradle-to-gate production impacts of pesticide manufacture.

CFP distinguishes between pesticide categories (herbicides, insecticides, fungicides, and mixed formulations) and applies crop-specific emission factors where available. These factors capture emissions associated with raw material extraction, chemical synthesis, formulation, and packaging of pesticide products. Where an exact match between crop and product is not available in the database, CFP applies a conservative approach by selecting the most representative or highest available emission factor.

Only emissions associated with pesticide production are included in this category. Emissions from machinery used for pesticide application (e.g., sprayers, tractors) are accounted for separately under the fuel and energy use module. This ensures a consistent and transparent separation between chemical input emissions and operational energy emissions.

PESTICIDE

Unit: kg CO_2-eq per kg GBE

Brazil Arabica	0.003
Brazil Robusta	0.004
Colombia	0.005
Honduras	0.009
Mexico	0.0004
Peru	0.001
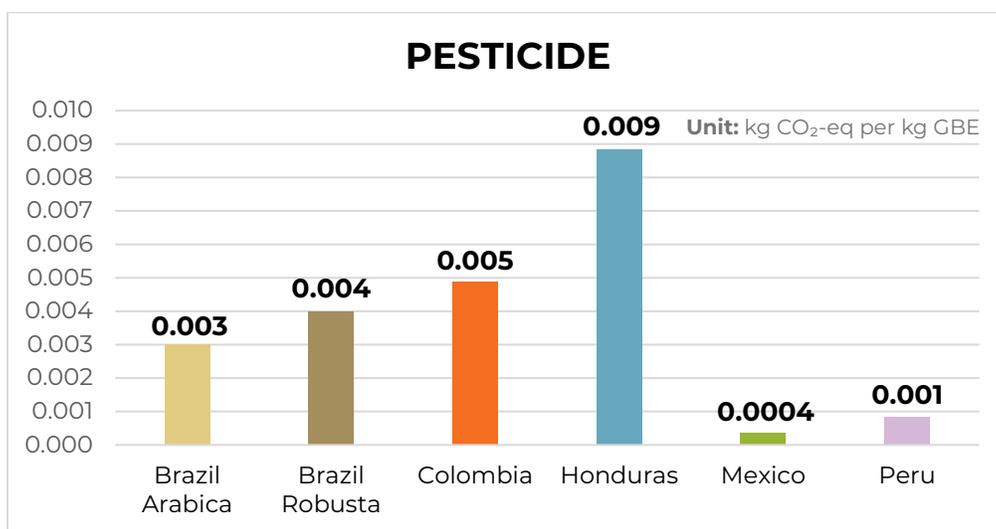
Figure 14: Breakdown of pesticide use emissions by countries

5.3.2. RESULTS FOR BRAZIL ARABICA

Pesticide use contributed only marginally to the overall carbon footprint of the Brazilian Arabica coffee supply chain up to farm-gate. Total emissions associated with pesticide use amounted to 302,395.2 kg CO_2-eq, corresponding to approximately 0.1% of total emissions when expressed per kg GBE.

Z-score analysis based on pesticide emissions per kg GBE shows that only 17 farms exhibit elevated value above mean. This confirms that pesticide use remains a minor

contributor to the overall farm-gate carbon footprint and does not materially influence aggregate emission results.

5.3.3. RESULTS FOR BRAZIL ROBUSTA

Pesticide use contributes only marginally to the Brazilian Robusta farm-gate carbon footprint, accounting for approximately 0.004 kg CO_2-eq per kg GBE—well below 1% of total emissions. In absolute terms, this is negligible compared to dominant sources such as fertilizers, crop residue management, and energy use.

Z-score analysis shows that pesticide emissions are concentrated within a small subset of farms, with 9-12 farms exceeding a Z-score of 2 depending on normalization. These farms consistently display higher pesticide intensity and excluding them reduces pesticide-category emissions by about 15%. However, given the very small overall contribution of pesticides to total emissions, their influence on national-level results remains limited, indicating that pesticides are a comparatively minor mitigation lever relative to higher-impact sources.

5.3.4. RESULTS FOR COLOMBIA

Pesticide use represented a minor source of GHG emissions in the Colombian coffee supply chain up to farm-gate. Total emissions from pesticide use amounted to 23,081.45 kg CO_2-eq, corresponding to 0.005 kg CO_2-eq per kg GBE and contributing approximately 0.1% to total farm-gate emissions.

Z-score analysis confirms that these results are not driven by a small number of extreme values. Only 9 out of 600 farms (2%) exhibit values above the mean when emissions are expressed per unit of output. A similar proportion is observed when comparing Z-scores against farm inputs. Pesticide-related emissions remain

negligible at the supply-chain level and do not materially affect the representativeness of the dataset or the overall carbon footprint.

5.3.5.   RESULTS FOR HONDURAS

Pesticide use was a small contributor to GHG emissions in the Honduran coffee supply chain up to farm-gate. Total pesticide-related emissions amounted to 44,179.4 kg CO_2-eq, corresponding to approximately 0.18% of total farm-gate emissions.

Z-score analysis confirms that only 5 out of 601 farms (1%) exhibit elevated values, and only 2 farms show elevated emissions when expressed per kg GBE. These results demonstrate that pesticide use has a negligible influence on the overall carbon footprint of Honduran coffee production and does not materially affect aggregate emission outcomes.

5.3.6.   RESULTS FOR MEXICO

Pesticide use had only a marginal impact on the overall carbon footprint of the Mexican coffee supply chain up to farm-gate. Total emissions from pesticide use were 1,629.8 kg CO_2-eq, corresponding to 0.0003 kg CO_2-eq per kg GBE and contributing approximately 0.05% to total emissions.

Z-score analysis shows that 16 out of 605 farms (2.6%) exhibit elevated values, while 21 farms (3.5%) show elevated Z-scores when emissions are expressed per unit of output. These 21 farms account for most emissions within this category, reflecting the limited use of pesticides across the sample, with only 77 farms reporting pesticide application. As a result, Z-scores are disproportionately elevated among pesticide-using farms, while overall pesticide-related emissions remain negligible at the supply-chain level.

5.3.7. RESULTS FOR PERU

Pesticide use played a very limited role in the overall carbon footprint of the Peruvian coffee supply chain. Total emissions from pesticide use amounted to 2,055.53 kg CO_2-eq, corresponding to 0.001 kg CO_2-eq per kg GBE and contributing approximately 0.03% to total emissions.

Z-score analysis indicates that 15 out of 600 farms (2%) exhibit values above the mean. When compared against farm size, 32 farms (5%) exceed the mean, and when expressed per unit of output, 27 farms are above the mean. Most deviations are only slightly above a Z-score of 2 and are primarily driven by reporting structure, as the majority of farms reported no pesticide use. Farms reporting multiple applications were therefore flagged as outliers even at low absolute volumes. Overall, pesticide-related emissions remain negligible and do not compromise the representativeness of the baseline or the overall carbon footprint.

5.4. CROP RESIDUE MANAGEMENT

5.4.1. OVERVIEW

In CFP, GHG emissions from crop residues in coffee production systems are modeled using a biomass-based, process-oriented framework that is consistent with IPCC guidance and LCA principles. Crop residue management represents a major source of emissions in coffee systems and encompasses the handling and treatment of coffee fruit waste, dead plants, above-ground biomass (AGB), below-ground biomass (BGB), dead organic matter (DOM), pruning residues, and primary coffee processing by-products such as pulp and husk. The CFP methodology is designed to reflect how biomass is generated throughout the coffee crop life cycle, how it is partitioned into distinct residue pools, and how each residue stream is subsequently managed at the farm level. Emissions are then quantified based on the physical and biochemical characteristics of each residue type and the management pathway applied by farmers.

Residue creation in coffee systems is modeled by first estimating total AGB and BGB production using a combination of age-dependent biomass function (for pruned biomass, leaf litter, and dead plant based on coffee trees per farm) and yield-based equations (for pulp, husk, and waste fruits based on fresh coffee cherries).

Once residue quantities are established, CFP allocates each residue stream to one or more management pathways based on farmer-reported practices. In CFP coffee systems, these management options include (1) leaving residues on the field as mulch, (2) composting residues either in heaps or pits (3) composting residues in aerated/non-aerated composting systems, (4) open-field burning of residue biomass, and (5) export of residues such as wood for use as fuel or timber. In a subsequent step, CFP distributes each residue stream across user-reported management pathways such as leaving residues on the field, composting (aerobic or anaerobic), storage in heaps or pits, burning, or export, using percentage shares that sum to 100% for each residue type. This proportional allocation enables the model to represent mixed and region-specific residue management strategies and directly links residue generation to on-farm treatment practices, thereby capturing how management decisions influence decomposition conditions and the resulting GHG emissions.

Emissions are calculated based on the quantity of biomass allocated to each management pathway and the corresponding emission factors associated with that pathway. The main emission processes captured by CFP include N_2O emissions from nitrogen mineralization during residue decomposition on soil and in composting systems, and CH_4 emissions from anaerobic decomposition in residue heaps, pits, and processing waste piles. CH_4 formation is particularly relevant for coffee systems due to the high moisture content of freshly washed coffee pulp and wastewater sludge, which create oxygen-limited conditions favorable for methanogenic activity. Warm climatic conditions typical of coffee-growing regions further intensify CH_4 formation. In parallel, N_2O emissions arise during microbial nitrification and denitrification processes acting on nitrogen contained in residues. These include both direct N_2O emissions released during on-site decomposition, and indirect N_2O emissions associated with nitrogen losses via volatilization and leaching, which subsequently lead to N_2O formation.

The magnitude of residue-related emissions is influenced by both the biophysical characteristics of the biomass and the residue management pathway applied. For residues that remain in situ, particularly BGB and residues incorporated into or left on the soil, emissions are strongly driven by the nitrogen content of the biomass, which varies substantially across residue types such as pruning wood, AGB, and BGB. In these cases, nitrogen contained in the residues undergoes mineralization and is subject to site-specific environmental conditions, including moisture, temperature, oxygen availability, and management practices, which together influence CO_2, N_2O, and, under anaerobic conditions, CH_4 emissions.

For other residue management options, such as composting or burning, CFP applies emission factors based on the total mass of residues managed. Emission estimates for these pathways are derived from emission factors reported in peer-reviewed literature, IPCC methodologies, and CFP's internal datasets and are calibrated to reflect the

higher global warming potential of CH_4 relative to CO_2 where applicable. Where management conditions are conducive to anaerobic decomposition, CFP explicitly accounts for CH_4 emissions in addition to CO_2 and N_2O.

Biogenic carbon dioxide released during residue burning is treated as out-of-scope in accordance with IPCC and GHGP conventions, as this carbon originates from short-cycle biomass and does not represent a net addition of carbon to the atmosphere. Residues that are exported off-farm, such as timber or fuelwood from old coffee trees, are not assigned emissions within the farm boundary. In these cases, responsibility for emissions shifts to the receiving system in accordance with life-cycle accounting principles, ensuring that emissions are not double-counted and that system boundaries remain consistent.

The results are expressed in CO_2-eq using IPCC global warming potential. Under Assessment Report 6[20], N_2O has a GWP100 of 273, and CH_4 a GWP100 of 27 for biogenic/non-fossil CH_4 and 29.8 for fossil CH_4, underscoring why even modest N_2O and CH_4 fluxes from residues can materially influence final emission values. The final emissions are reported in terms of kg CO_2-eq per kg GBE. To assess data robustness and the influence of extreme values, the results are further evaluated using a Z-score analysis, allowing non-homogeneity to be identified without compromising the representativeness of aggregated outcomes.
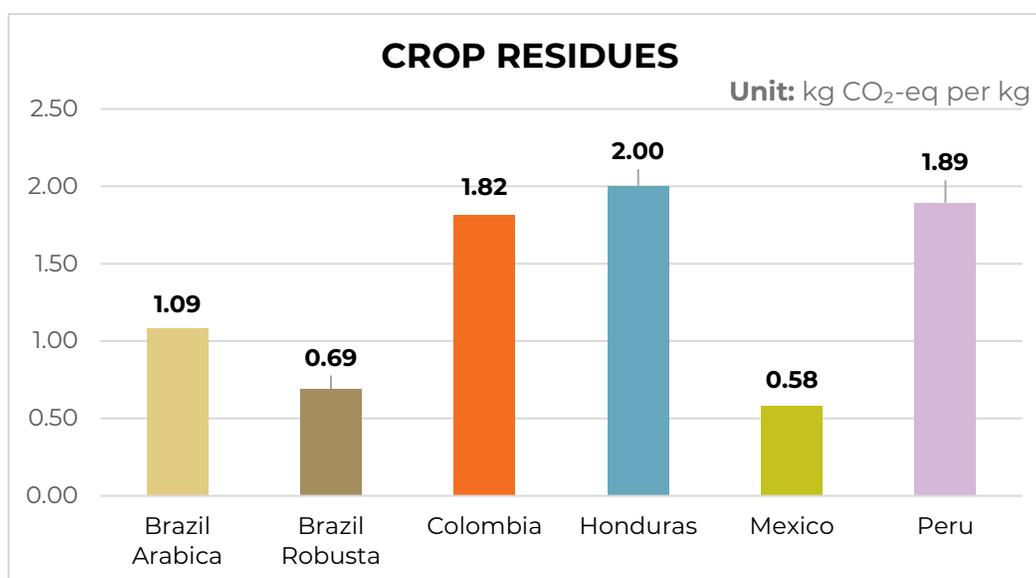
Figure 15: Breakdown of crop residue emissions by countries

[20] Intergovernmental Panel on Climate Change. (2023). Sections. In H. Lee & J. Romero (Eds.), Climate change 2023: Synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 35–115). IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647

5.4.2. RESULTS FOR BRAZIL ARABICA

In the Brazilian Arabica coffee supply chain, crop residue management represents a major source of GHG emissions up to the farm gate. Total emissions from crop residues amount to 108,883,537.7 kg CO_2-eq, corresponding to 1.09 kg CO_2-eq per kg GBE and representing approximately 34% of total farm-gate emissions.

The residue emission profile shows an even split between N_2O and CH_4, each contributing 50% of total residue-related emissions. This balanced contribution reflects the coexistence of widespread field-based residue decomposition processes alongside anaerobic residue handling and burning practices.

Z-score analysis confirms that these results are not driven by a small number of extreme values and that the dataset is statistically robust. When residue management emissions are evaluated per ha, only 32 out of 500 farms (6%) exhibit an elevated Z-score greater than 1. When normalized by production (kg GBE), the number decreases to 16 farms (3%). Although two farms display exceptionally high Z-scores associated with pruning and leaf litter management, their influence on aggregated results is negligible, confirming that crop residue emissions are a consistent and structurally embedded feature of the Brazilian Arabica supply chain.

The reported residue treatment patterns provide important context for the observed emission structure. Export, although disclosed by a number of farms, is considered irrelevant for the scope of this study as it is outside the system boundary, so further exploration of this context focuses on the residue treatments that fall within the system boundary.

For pruning residues, the dominant management practice is leaving biomass on the field, reported by 155 farms, followed by open burning by 12 farms. The relatively low number of farms reporting pruning residues indicates that a majority of farms did not conduct pruning during the assessment year, reflecting management cycles rather than irrelevance of pruning residue reporting. For leaf litter, residue management is overwhelmingly field-based, with 490 farms reporting that litter is left on the soil surface, while only a very small number of farms apply anaerobic composting (4 farms) or aerobic composting (2 farms). A similar pattern is observed for coffee pulp and husk, where 372 farms report leaving residues on the field, followed by 62 farms applying aerobic composting and 39 farms using heaps or pits.

FREQUENCY OF PRUNING WASTE DISPOSAL PRACTICES - BRAZIL ARABICA

Practice	Value
Export	69%
Left on field	31%
Anaerobic compost	0%
Aerobic compost	0%
Heaps or pits (off the field)	0%
Burn	2%
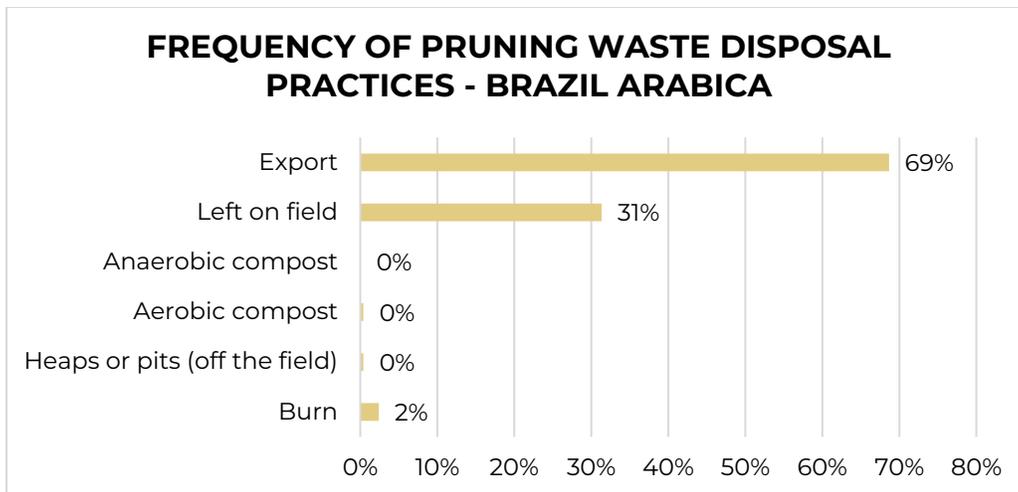
Figure 16. Frequency of Pruning Waste Disposal Practices - Brazil Arabica

Overall, these treatment patterns indicate that residue management in Brazil's Arabica value chain is strongly dominated by low-intervention field-based pathways, with limited uptake of composting practices across most residue streams. The widespread practice of leaving residues on the field sustains N_2O emissions through nitrogen mineralization, while the continued use of burning and anaerobic residue handling contributes to CH_4 emissions, resulting in the observed emission profile. The combination of high residue volumes, infrequent pruning cycles, and consistent residue handling practices across farms explains both the magnitude and stability of crop residue emissions in Brazilian Arabica coffee production up to the farm-gate and highlights residue management as a structurally embedded mitigation hotspot.

FREQUENCY OF LEAF LITTER DISPOSAL PRACTICES - BRAZIL ARABICA

Practice	Value
Left on field	99%
Anaerobic compost	1%
Aerobic compost	0%
Heaps or pits (off the field)	0%
Burn	0%
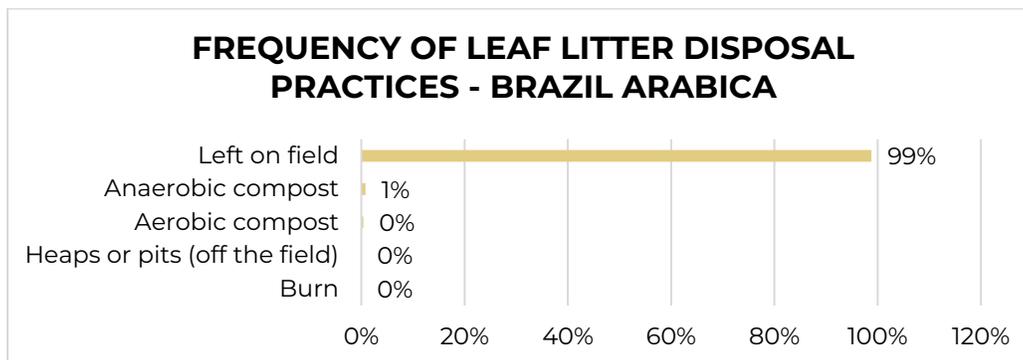
Figure 17 Frequency of Leaf Litter Disposal Practices - Brazil Arabica

From a mitigation perspective, these results suggest that improving residue handling practices rather than reducing residue quantities offers the greatest emission reduction potential. Avoiding open burning of pruning residues, expanding aerobic composting for pulp and husk to generate fertilizer, and improving aeration and moisture management where residues are piled would directly reduce CH_4 emissions, while optimizing the distribution and timing of field-applied residues could moderate N_2O formation. Given the consistency of current practices across farms, such measures

represent scalable mitigation opportunities with limited risk to productivity and strong co-benefits for soil health.

FREQUENCY OF COFFEE PULP OR HUSKS DISPOSAL PRACTICES - BRAZIL ARABICA
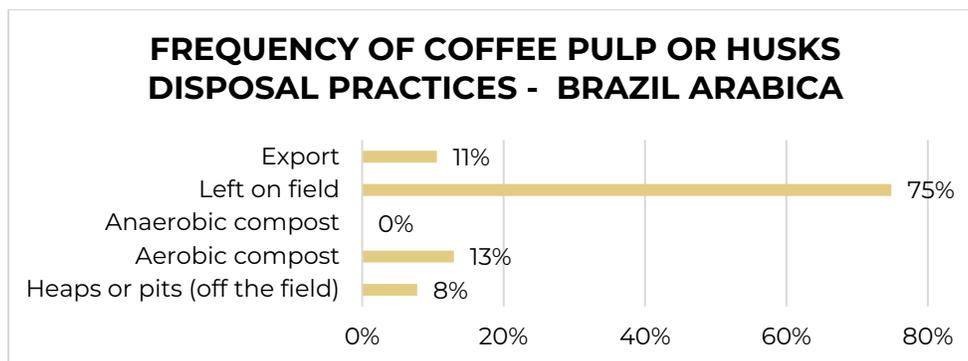
Figure 18. Frequency of Coffee Pulp or Husks Disposal Practices - Brazil Arabica

5.4.3. RESULTS FOR BRAZIL ROBUSTA

In the Brazilian Robusta coffee supply chain, crop residue management represents a major source of farm-gate GHG emissions. Total emissions from crop residues amount to 33,852,977.52 kg CO_2-eq, corresponding to 0.69 kg CO_2-eq per kg GBE and representing 27.43 % of total farm-gate emissions. Crop residues, therefore, constitute the second most important emission source in Brazilian Robusta production up to farm-gate, following mineral fertilizer use.

Residue-related emissions are dominated by N_2O, which accounts for 66% of total crop residue emissions, while CH_4 contributes 34%. This emission profile reflects the predominance of field-based residue decomposition processes, which sustain N_2O emissions through nitrogen mineralization, alongside a smaller but still relevant contribution from burning and anaerobic residue handling, which generate CH_4. Compared with Arabica systems, the Robusta residue profile is therefore more strongly weighted toward N_2O-driven processes.

Z-score analysis indicates that crop residue emissions exhibit moderate heterogeneity, largely associated with pruning practices. When emissions are evaluated on a per-ha basis, 23 farms exhibit elevated Z-scores greater than 2, increasing to 29 farms when emissions are normalized per kg GBE. The same farms consistently appear across both normalization approaches, indicating structurally higher residue-related emissions

rather than artifacts of scaling. These higher values are systematically linked to pruning-related emissions, confirming pruning as the primary driver of variability within the residue category.

FREQUENCY OF PRUNING WASTE DISPOSAL PRACTICES - BRAZIL ROBUSTA

Practice	Value
Export	1%
Left on field	91%
Anaerobic compost	0%
Aerobic compost	1%
Heaps or pits (off the field)	0%
Burn	0%
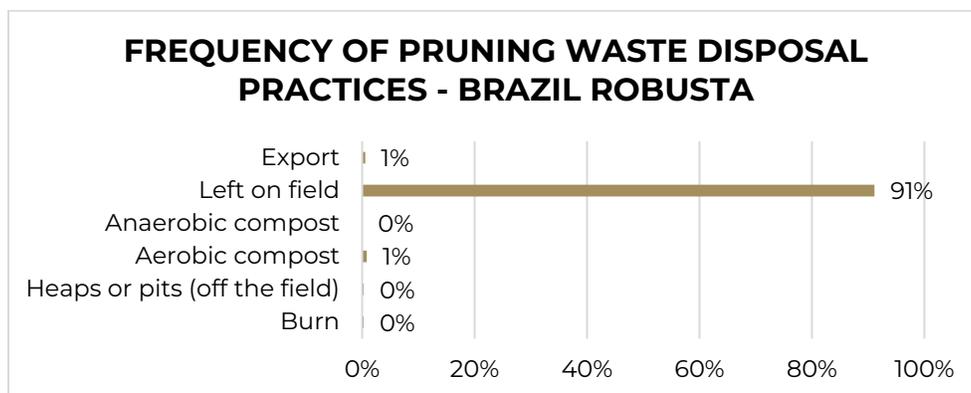
Figure 19. Frequency of Pruning Waste Disposal Practices - Brazil Robusta

Reported residue management practices provide important context for these patterns. Pruning residues are predominantly left on the field, reported by 338 farms, while open burning is extremely rare, reported by 1 farm, and 3 farms report removal or composting. Leaf litter management is also overwhelmingly field-based, with 244 farms reporting that litter is left on the soil surface. For coffee pulp and husk, the dominant practice remains field application, reported by 282 farms, followed by anaerobic heaps or pits reported by 37 farms, and export of residues reported by 80 farms, while aerobic composting is reported by only 1 farm. Together, these patterns indicate that residue management in Brazilian Robusta systems is strongly characterized by low-intervention, field-based pathways, with limited adoption of controlled composting practices.

FREQUENCY OF LEAF LITTER DISPOSAL PRACTICES - BRAZIL ROBUSTA

Practice	Value
Left on field	66%
Anaerobic compost	0%
Aerobic compost	0%
Heaps or pits (off the field)	0%
Burn	0%
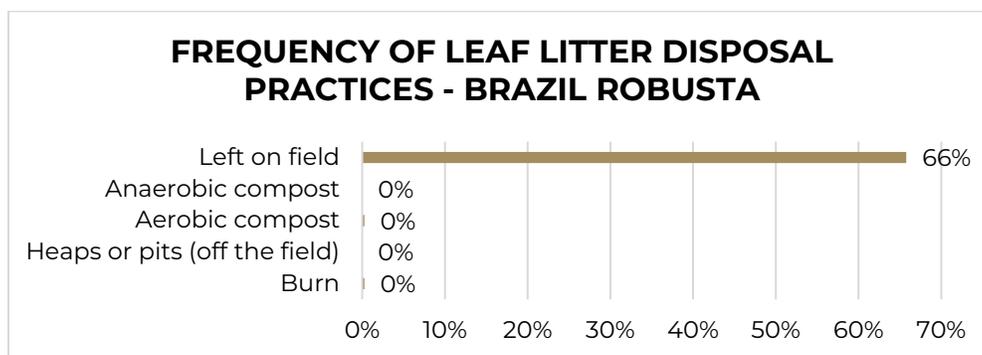
Figure 20: Frequency of Leaf Litter Disposal Practice - Brazil Robusta

Overall, the magnitude and relative stability of crop residue emissions in Brazilian Robusta production appear to be associated with large biomass volumes, the predominance of field-based residue handling, and broadly consistent management practices across farms, despite observable heterogeneity linked to pruning intensity. From a mitigation perspective, the results suggest that changes in residue handling

practices may represent a relevant area for further exploration, particularly in relation to reducing CH_4 formation from anaerobic pathways and moderating N_2O emissions associated with residue mineralization. Approaches such as increased use of aerobic composting for pulp and husk and improved timing and distribution of field-applied residues could be considered in future assessments, while recognizing the need to balance emission outcomes with agronomic feasibility and soil health benefits.

FREQUENCY OF COFFEE PULP OR HUSKS DISPOSAL PRACTICES - BRAZIL ROBUSTA

Practice	Percentage
Export	22%
Left on field	76%
Anaerobic compost	0%
Aerobic compost	4%
Heaps or pits (off the field)	10%
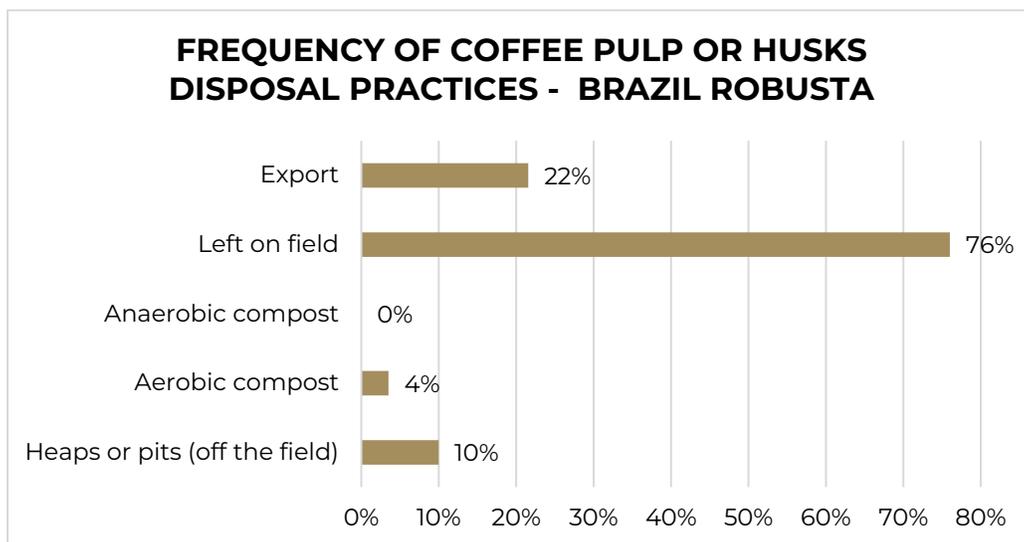
Figure 21: Frequency of Coffee Pulp or Husks Disposal Practices - Brazil Robusta

5.4.4. RESULTS FOR COLOMBIA

In the Colombian coffee supply chain, crop residue management constitutes a major source of GHG emissions at the farm gate. Total emissions from crop residues amount to 8,567,974.49 kg CO_2-eq, corresponding to 1.82 kg CO_2-eq per kg GBE and representing approximately 33% of total farm-gate emissions.

The emission profile is dominated by N_2O, which accounts for 74% of the residue-related emissions, while CH_4 accounts for the remaining 26%. This distribution reflects the predominance of nitrogen mineralization processes that drive N_2O formation, followed by CH_4 emissions, which arise primarily from anaerobic conditions in residue heaps and pits.

FREQUENCY OF PRUNING WASTE DISPOSAL PRACTICES - COLOMBIA

Export — 62%
Left on field — 18%
Anaerobic compost — 0%
Aerobic compost — 1%
Heaps or pits (off the field) — 17%
Burn — 5%

Figure 22. Frequency of Pruning Waste Disposal Practices - Colombia

Z-score analysis confirms that these results are not driven by a small number of extreme values and that the dataset is statistically robust. When residue management emissions are evaluated at the farm level, only 16 out of 600 farms (3%) exhibit an elevated Z-score greater than 1. When the emissions are normalized by production (kg GBE), the number decreases further to only 3 farms (0.5%), and when assessed on a per-ha basis, only 9 farms (1.5%) show elevated Z-scores greater than 1. These proportions are statistically negligible and confirm that crop residue emissions are a consistent and structurally embedded feature of the Colombian coffee production system.

The reported residue treatment patterns provide a clear explanation for the observed emission structure. For pruning residues, the dominant management practice is leaving biomass on the field, reported by 110 farms, followed by storage in heaps or pits by 98 farms and open burning by 32 farms. For leaf litter, residue management is almost entirely field-based, with 596 farms reporting that litter is left on the soil surface, while only 10 farms use aerobic composting and 3 farms manage litter in heaps or pits. A similar pattern is observed for coffee pulp and husk, where 501 farms report leaving residues on the field, followed by 129 farms using heaps or pits, and 55 farms applying aerobic composting.

**FREQUENCY OF LEAF LITTER DISPOSAL
PRACTICES - COLOMBIA**

Practice	Value
Left on field	100%
Anaerobic compost	0%
Aerobic compost	1%
Heaps or pits (off the field)	1%
Burn	0%
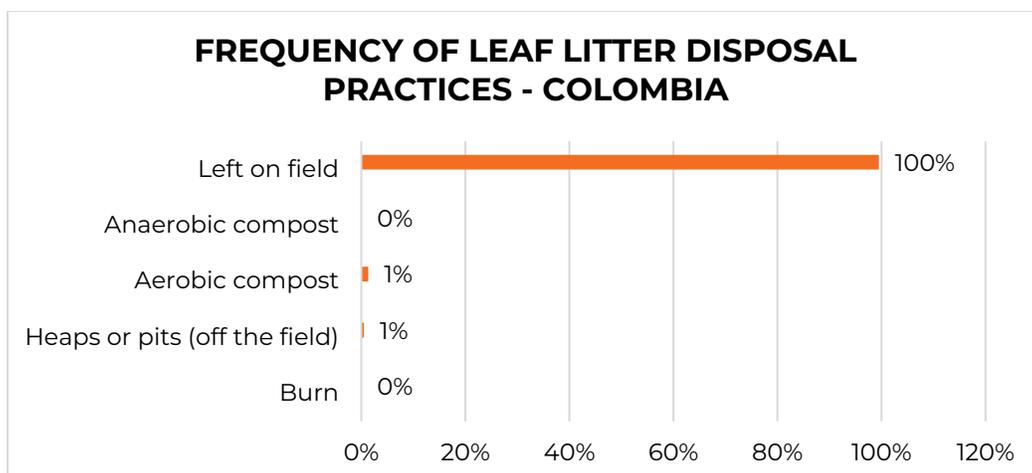
Figure 23. Frequency of Leaf Litter Disposal Practices - Colombia

Overall, these treatment patterns demonstrate that residue management in Colombia is overwhelmingly dominated by low-intervention field-based decomposition pathways with leaving the residues on the field. While this promotes nutrient recycling and replenishment of soil organic matter, it also explains the dominance of N_2O emissions in the residue emission profile, driven by sustained nitrogen mineralization under warm, humid conditions. At the same time, the continued use of heaps and pits for pulp and pruning residues creates anaerobic micro-environments that drive the observed CH_4 emissions. The consistency of these practices across the supply chain explains both the magnitude and the stability of crop residue emissions in Colombian coffee production and highlights residue management as a structurally embedded mitigation hotspot.

Mitigation should therefore focus on improving residue management practices rather than reducing residue quantities, which are inherent to coffee production systems. Indeed, given that 74% of residue related emissions are attributable to N_2O, the most effective mitigation measures relate to optimizing nitrogen dynamics during residue decomposition. Improving residue distribution, reducing mulching thickness, and better synchronizing residue application with crop nitrogen demand can moderate nitrogen mineralization and associated N_2O formation while maintaining soil fertility benefits.

For coffee pulp and husk, the continued use of heaps and pits creates anaerobic conditions that drive CH_4 emissions. Shifting these residues toward aerobic composting through improved aeration, turning, and moisture control offers a scalable pathway to reduce CH_4 emissions while stabilizing nutrients. For pruning residues, avoiding open burning and promoting mulching or controlled composting would eliminate combustion-related emissions and enhance soil cover. Overall, mitigation should prioritize practice improvements supported by targeted training

and extension, as consistent management patterns across farms indicate strong potential for scalable emission reductions with co-benefits for soil health.

FREQUENCY OF COFFEE PULP OR HUSKS DISPOSAL PRACTICES - COLOMBIA
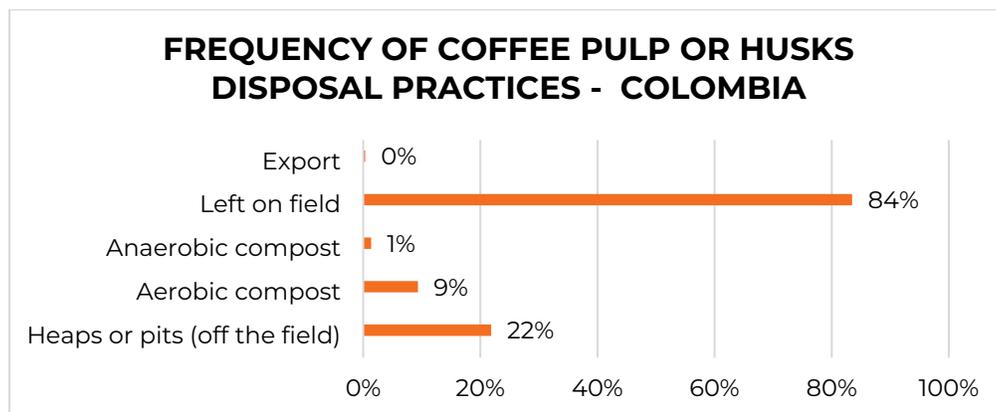
Figure 24. Frequency of Coffee Pulp or Husks Disposal Practices - Colombia

5.4.5. RESULTS FOR HONDURAS

In the Honduran coffee supply chain, crop residue management constitutes a significant source of GHG emissions at the farm gate. Total emissions from crop residues amount to 10,001,801 kg CO_2-eq, corresponding to 2.00 kg CO_2-eq per kg GBE and representing approximately 41% of total farm-gate emissions.

The emission profile is moderately dominated by N_2O, which accounts for 57% of residue-related emissions, while CH_4 contributes the remaining 43%. Compared to Colombia, Honduras exhibits a substantially higher CH_4 share, and compared to Brazil Arabica, a clearer dominance of N_2O, reflecting a mixed residue management system where both aerobic field-based decomposition and anaerobic handling pathways are widely practiced.

Z-score analysis confirms that these results are not driven by a small number of extreme values. When residue management emissions are evaluated on a per-ha basis, only 5 out of 601 farms (1%) exhibit an elevated Z-score greater than 1, while normalization by production (kg GBE) identifies 9 farms (1.5%) with elevated values. Although a very small number of farms display exceptionally high emissions linked to dead-tree management and pruning losses, their overall influence on aggregated results remains statistically negligible. This confirms that crop residue emissions in

Honduras are a structurally embedded feature of the production system rather than the result of isolated management practices.

The reported residue treatment patterns explain the comparatively high CH_4 contribution and differentiate Honduras clearly from both Brazil Arabica and Colombia. For pruning residues, the dominant management practice is leaving biomass on the field, reported by 309 farms, followed by open burning by 74 farms and management in heaps or pits by 35 farms. Leaf litter management remains largely field-based, with 402 farms leaving litter on the soil surface; however, a substantial number of farms (278) manage leaf litter in heaps or pits, a practice far less common in Brazil Arabica and Colombia and one that directly contributes to anaerobic decomposition. The most pronounced contrast is observed for coffee pulp and husk, where heaps or pits represent the dominant treatment pathway, reported by 290 farms, followed closely by leaving residues on the field (280 farms) and aerobic composting (137 farms).

FREQUENCY OF PRUNING WASTE DISPOSAL PRACTICES - HONDURAS

Practice	Percentage
Export	7%
Left on field	51%
Anaerobic compost	0%
Aerobic compost	1%
Heaps or pits (off the field)	5%
Burn	12%

Figure 25. Frequency of Pruning Waste Disposal Practices - Honduras

Overall, these treatment patterns indicate that Honduras relies far more heavily on anaerobic residue handling than either Brazil Arabica or Colombia, particularly for processing residues and leaf litter. This explains the elevated share of CH_4 emissions in the Honduran residue emission profile and distinguishes Honduras from Brazil Arabica, where residues are predominantly left on the field, and from Colombia, where field-based decomposition dominates with more limited use of heaps and pits. While the widespread practice of leaving residues on the field sustains N_2O emissions through nitrogen mineralization, the extensive use of heaps and pits creates anaerobic micro-environments that substantially increase CH_4 formation. The consistency of these practices across farms explains both the magnitude and stability of residue-related emissions in Honduran coffee production and highlights residue management as a critical mitigation hotspot.

**FREQUENCY OF LEAF LITTER DISPOSAL
PRACTICES - HONDURAS**

Left on field — 64%
Anaerobic compost — 0%
Aerobic compost — 0%
Heaps or pits (off the field) — 9%
Burn — 0%
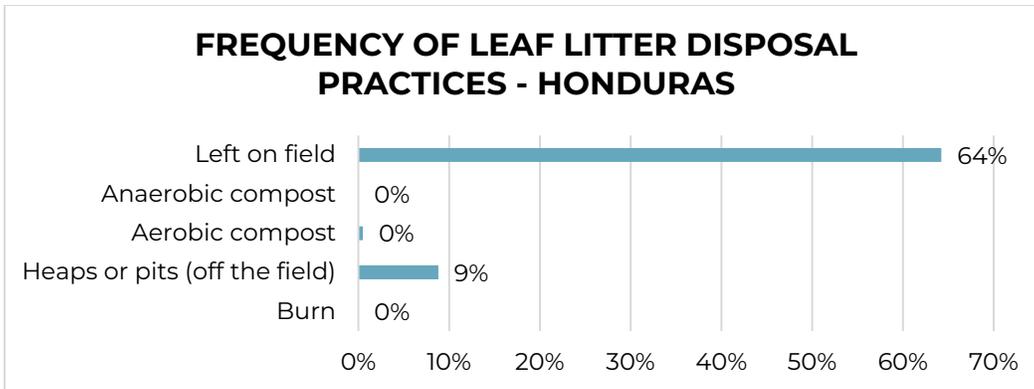
Figure 26. Frequency of Leaf Litter Disposal Practices - Honduras

From a mitigation perspective, Honduras presents particularly strong opportunities to reduce CH_4 emissions by transitioning pulp, husk, and leaf litter management away from unmanaged heaps and pits toward aerobic composting or improved field application practices. Compared to Brazil Arabica, where mitigation must address low adoption of composting, and Colombia, where mitigation focuses primarily on optimizing field-based residue handling, Honduras would benefit most from structural improvements in residue treatment pathways, especially for processing residues. Expanding aerobic composting, improving aeration and moisture control in existing piles, and reducing open burning of pruning residues would directly target the dominant emission drivers, with strong potential for scalable emission reductions and co-benefits for nutrient management and soil health.

**FREQUENCY OF COFFEE PULP OR HUSKS
DISPOSAL PRACTICES - HONDURAS**

Export — 1%
Left on field — 47%
Anaerobic compost — 0%
Aerobic compost — 22%
Heaps or pits (off the field) — 13%

Figure 27. Frequency of Coffee Pulp or Husks Disposal Practices - Honduras

5.4.6. RESULTS FOR MEXICO

In the Mexican coffee supply chain, crop residue management constitutes a major source of GHG emissions at the farm gate, with an emission profile that most closely resembles Colombia, while remaining distinct from both Brazil Arabica and Honduras. Total **emissions from crop residues amount to 2,547,221.9 kg CO_2-eq, corresponding to 0.58 kg CO_2-eq per kg GBE and representing approximately 40% of total farm-gate emissions.**

The emission profile is dominated by N_2O, which accounts for 69% of residue-related emissions, while CH_4 contributes the remaining 31%. Compared to Brazil Arabica, where residue emissions are evenly split between N_2O and CH_4, and Honduras, where CH_4 plays a much larger role due to extensive anaerobic handling, Mexico exhibits a clearer dominance of N_2O, reflecting the prevalence of aerobic, field-based residue decomposition pathways.

Z-score analysis confirms that, as observed across the other origins, these results are not driven by a small number of extreme values. When residue management emissions are evaluated per unit of output (kg GBE), only 21 out of 620 farms (3%) exhibit an elevated Z-score greater than 1, while an area-based assessment identifies 32 farms (5%) with elevated values. Only a single farm displays exceptionally high Z-scores for pruning and leaf litter management; however, excluding this farm alters aggregated residue emissions by less than 0.3%, confirming that crop residue emissions in Mexico are a structurally embedded feature of the production system rather than the result of isolated management practices.

The reported residue treatment patterns explain the dominance of N_2O emissions and clearly differentiate Mexico from Honduras. For pruning residues, the dominant management practice is leaving biomass on the field, reported by 308 farms, followed by management in heaps or pits by 70 farms and aerobic composting by 24 farms. Leaf litter is similarly managed predominantly through field-based decomposition, with 570 farms leaving litter on the soil surface, while 115 farms manage litter in heaps or pits, and 63 farms apply aerobic composting. For coffee pulp and husk, residue management remains more mixed: 211 farms report leaving residues on the field, 203 farms manage residues in heaps or pits, and 82 farms apply aerobic composting.

FREQUENCY OF PRUNING WASTE DISPOSAL PRACTICES - MEXICO

Export — 6%
Left on field — 51%
Anaerobic compost — 0%
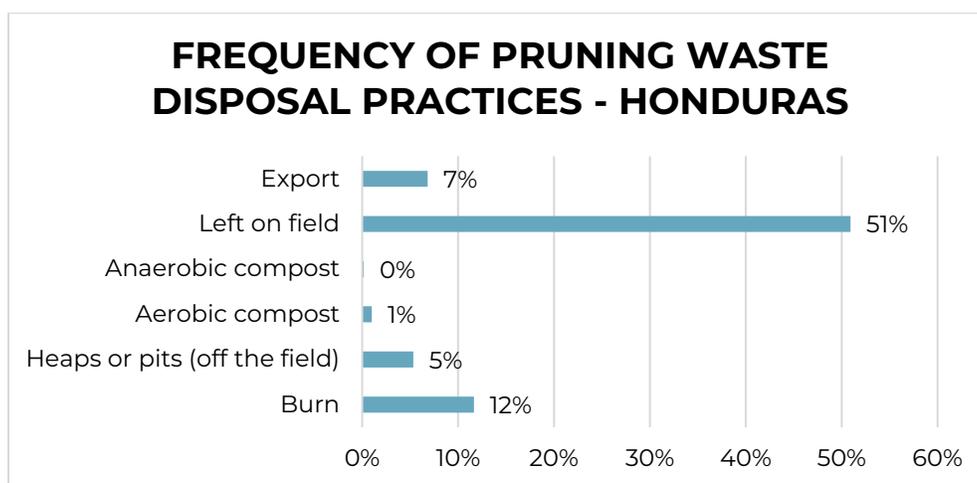Aerobic compost — 4%
Heaps or pits (off the field) — 14%
Burn — 1%
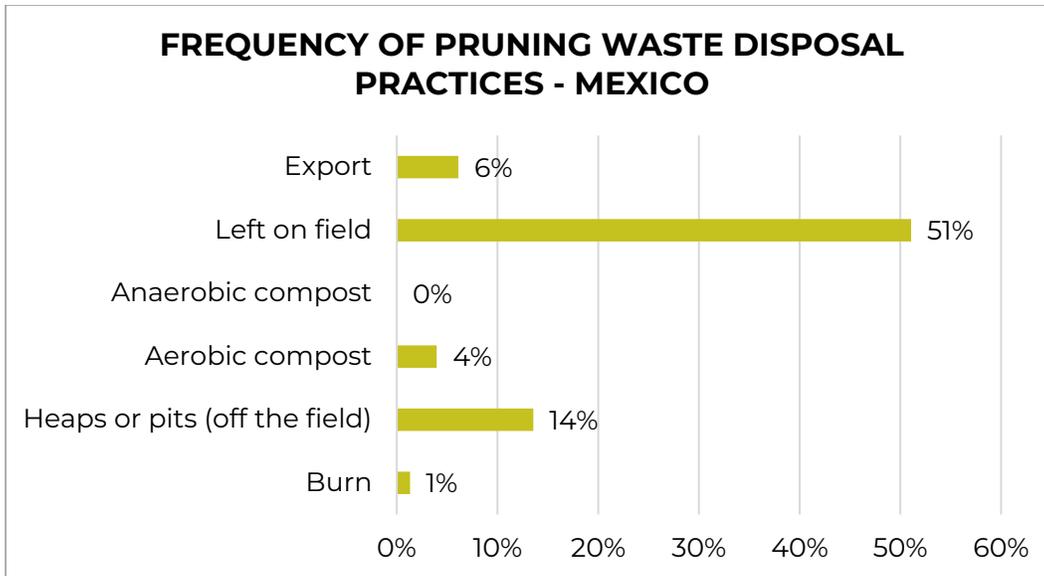
Figure 28. Frequency of Pruning Waste Disposal Practices - Mexico

Overall, these treatment patterns indicate that Mexico relies primarily on low-intervention field-based residue management, similar to Colombia, but with a greater use of heaps and pits for processing residues than observed in both Colombia and Brazil Arabica. This explains the continued contribution of CH_4 to the residue emission profile, while the dominance of field-based practices sustains N_2O emissions through nitrogen mineralization. Compared to Honduras, however, Mexico shows substantially lower reliance on anaerobic residue handling, resulting in a lower CH_4 share and a more N_2O-dominated emission profile. The consistency of these practices across farms explains both the magnitude and stability of crop residue emissions in Mexican coffee production and highlights residue management as a key, yet manageable, mitigation hotspot.

FREQUENCY OF LEAF LITTER DISPOSAL PRACTICES - MEXICO

Left on field — 69%
Anaerobic compost — 0%
Aerobic compost — 11%
Heaps or pits (off the field) — 19%
Burn — 0%
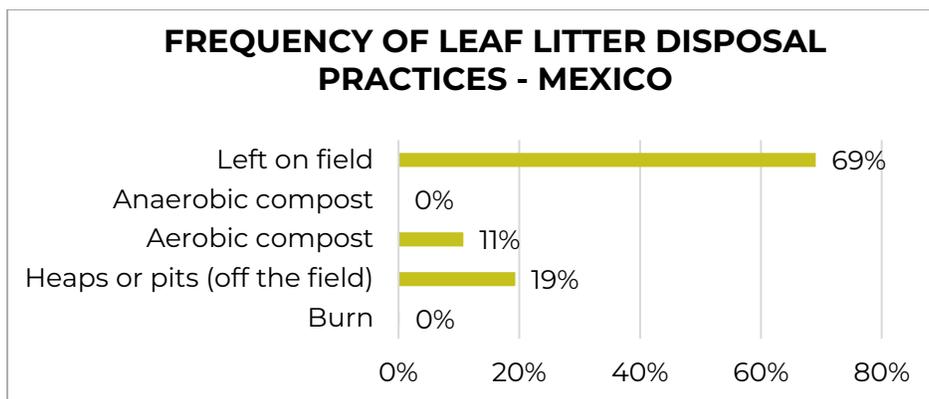
Figure 29. Frequency of Leaf Litter Disposal Practices - Mexico

From a mitigation perspective, Mexico is well positioned between Colombia and Honduras. The priority lies in reducing anaerobic handling of pulp and husk by shifting

residues from heaps and pits toward aerobic composting or improved field application, while optimizing residue distribution and timing for pruning and leaf litter to moderate nitrogen mineralization and associated N_2O formation. Compared to Brazil Arabica, where composting uptake remains limited, and Honduras, where structural changes in residue handling are required, Mexico presents a balanced opportunity for mitigation through incremental improvements to existing practices, with strong co-benefits for soil fertility and nutrient management.

FREQUENCY OF COFFEE PULP OR HUSKS DISPOSAL PRACTICES - MEXICO

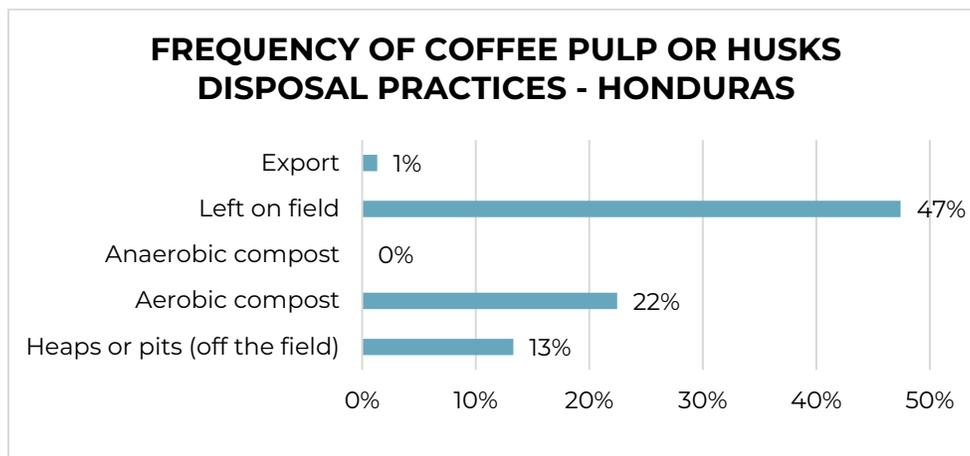| Category	Value
Export	3%
(unlabeled)	35%
Anaerobic compost	0%
(unlabeled)	14%
Heaps or pits (off the field)	34%
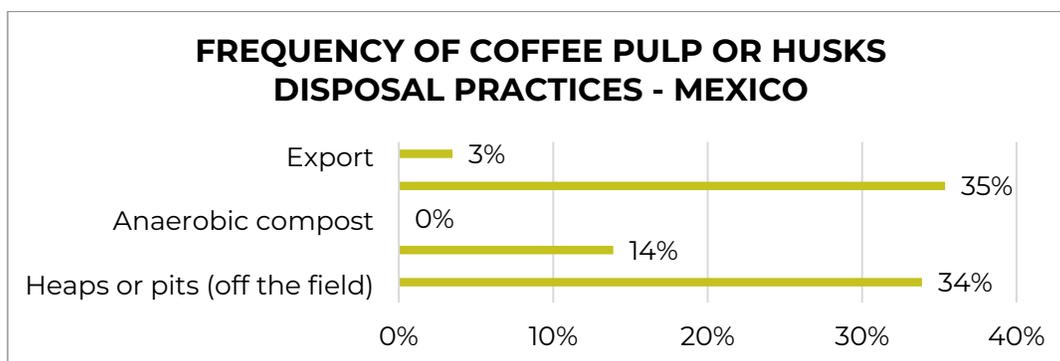
Figure 30. Frequency of Coffee Pulp or Husks Disposal Practices - Mexico

5.4.7. RESULTS FOR PERU

In the Peruvian coffee supply chain, crop residue management constitutes the single largest source of GHG emissions at the farm gate, distinguishing Peru clearly from the other assessed origins. Total emissions from crop residues amount to 4,619,328.17 kg CO_2-eq, corresponding to 1.89 kg CO_2-eq per kg GBE and representing approximately 66.5% of total farm-gate emissions.

This relative contribution is substantially higher than observed in Colombia and Mexico, comparable in magnitude to Honduras, and markedly higher than in Brazil Arabica. The residue emission profile is dominated by N_2O, which accounts for 61% of residue-related emissions, while CH_4 contributes the remaining 39%. Compared to Brazil Arabica, where N_2O and CH_4 contribute equally, and Honduras, where CH_4 which relatively plays a stronger role when compared to other countries due to extensive

anaerobic handling, Peru exhibits a more N_2O-weighted profile, reflecting greater reliance on aerobic residue management pathways.

Z-score analysis confirms that, consistent with findings for Colombia, Brazil Arabica, Honduras, and Mexico, these results are not driven by a small number of extreme values. When residue management emissions are evaluated at the farm level, only 25 out of 620 farms (4%) exhibit an elevated Z-score greater than 1. When emissions are normalized by coffee production (kg GBE), the number decreases slightly to 22 farms (3.5%), and when assessed on a per-ha basis, 29 farms (5%) show elevated Z-scores greater than 1. These proportions remain statistically negligible and indicate that crop residue emissions in Peru are, like the other countries, a structurally embedded feature of the production system rather than the result of isolated management practices.

The reported residue treatment patterns explain both the magnitude of residue emissions and Peru's distinct position among the assessed countries. Similar to Brazil Arabica, Colombia, and Mexico, pruning residues in Peru are predominantly managed by leaving biomass on the field, reported by 153 farms, followed by management in heaps or pits by 103 farms, and aerobic composting by 39 farms. Leaf litter management is overwhelmingly field based, with 619 farms leaving litter on the soil surface, a pattern consistent across all origins. In contrast to Brazil, Colombia, Honduras, and Mexico, however, coffee pulp and husk management in Peru is dominated by aerobic composting, reported by 544 farms, with substantially fewer farms leaving residues on the field (135 farms) or managing them in heaps or pits (55 farms).
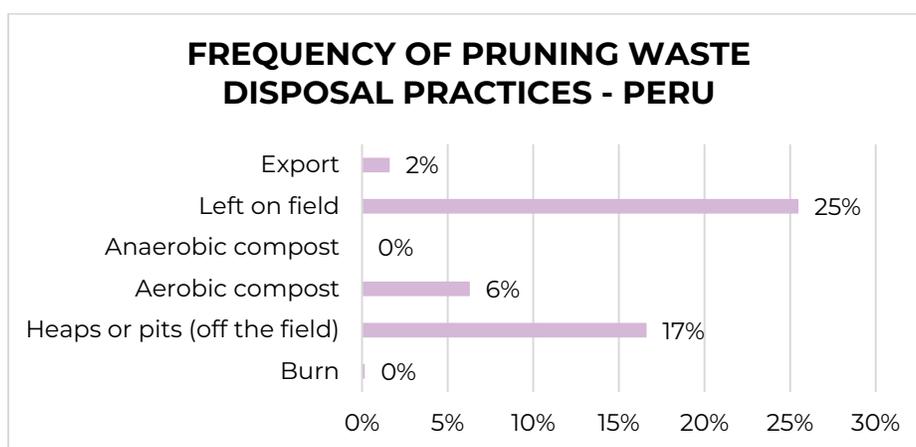
Figure 31. Frequency of Pruning Waste Disposal Practices - Peru

FREQUENCY OF LEAF LITTER DISPOSAL PRACTICES - PERU

Practice	Value
Left on field	65%
Anaerobic compost	0%
Aerobic compost	2%
Heaps or pits (off the field)	3%
Burn	1%
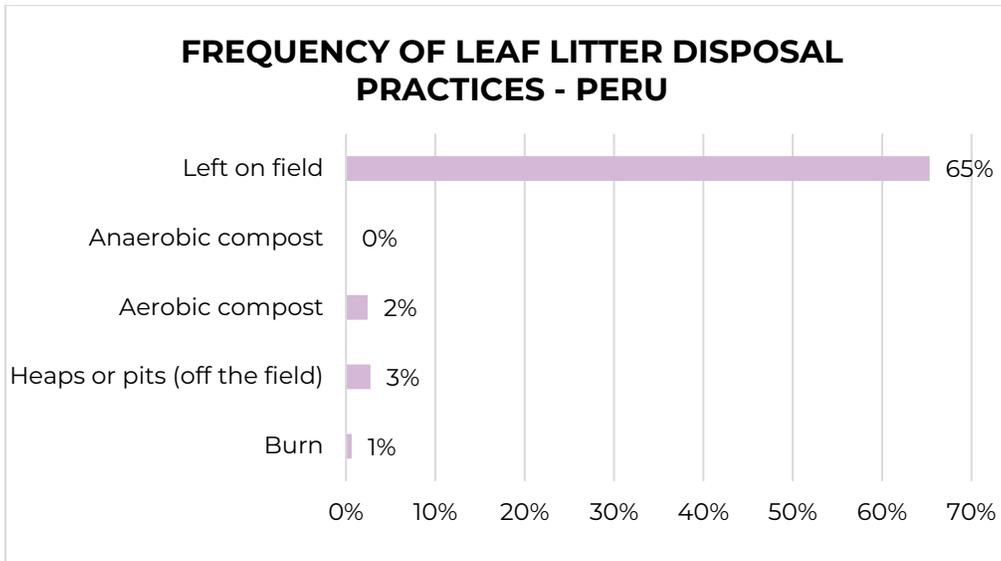
Figure 32. Frequency of Leaf Litter Disposal Practices - Peru

This widespread adoption of aerobic composting for processing residues clearly differentiates Peru from Honduras, where heaps and pits dominate pulp and husk management, and from Brazil Arabica and Colombia, where field-based decomposition remains prevalent. As a result, methane formation from processing residues is substantially constrained in Peru, explaining why CH_4 does not dominate the residue emission profile despite the large overall contribution of residues to total emissions. At the same time, the continued reliance on field-based decomposition for pruning and leaf litter sustains elevated N_2O emissions through nitrogen mineralization processes under favorable climatic conditions. The combination of high residue intensity, diversified residue management practices, and consistent behavior across farms explains both the scale and stability of crop residue emissions in Peruvian coffee production.

FREQUENCY OF COFFEE PULP OR HUSKS DISPOSAL PRACTICES - PERU

Practice	Value
Export	1%
Left on field	22%
Anaerobic compost	0%
Aerobic compost	88%
Heaps or pits (off the field)	18%
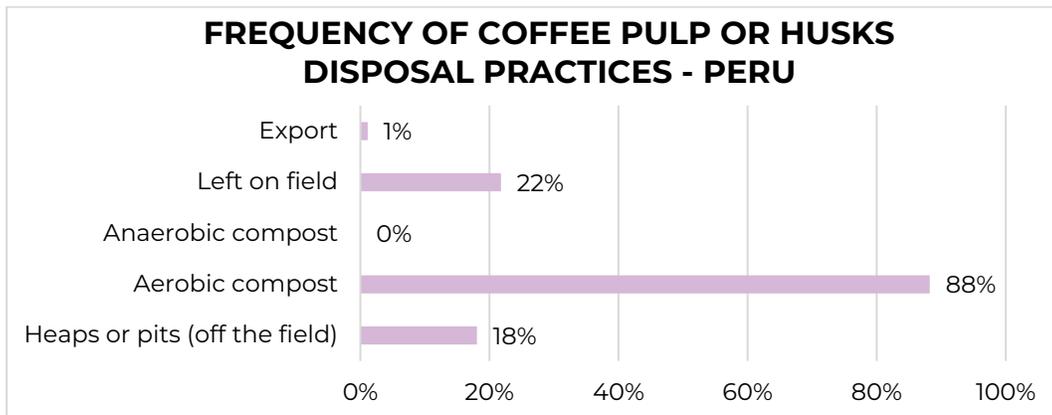
Figure 33. Frequency of Coffee Pulp or Husks Disposal Practices - Peru

From a mitigation perspective, Peru occupies a more advanced position than the other assessed origins. While Brazil Arabica, Colombia, Honduras, and Mexico require structural shifts away from unmanaged heaps, pits, or burning, Peru's primary mitigation potential lies in building on existing good practice. Expanding aerobic composting beyond pulp and husk to other residue streams, improving aeration and moisture control where heaps are still used, and optimizing the timing and distribution of field-applied residues would directly address both N_2O and residual CH_4 emissions. Compared to the other origins, these measures present relatively low implementation barriers and offer strong potential for scalable emission reductions with clear co-benefits for nutrient management and soil health.

5.4.8. CONCLUSIONS AND LIMITATIONS

Across the five coffee-producing countries assessed, crop residue management emerges as a structurally embedded and consistently significant source of GHG emissions up to farm-gate, although the magnitude and underlying drivers vary markedly by origin. Brazil Arabica and Colombia are characterized by predominantly field-based residue management, resulting in emission profiles dominated by N_2O from nitrogen mineralization, with CH_4 playing a more limited role except where burning or anaerobic handling occurs. Peru stands out for the exceptionally high relative contribution of residues to the total footprint, driven by large residue volumes but moderated by widespread adoption of aerobic composting for processing residues, which constrains CH_4 formation despite the scale of emissions. Honduras exhibits the strongest influence of anaerobic residue handling, particularly for pulp, husk, and leaf litter, leading to a substantially higher CH_4 share and highlighting structural gaps in residue treatment infrastructure. Mexico occupies an intermediate position, with residue management largely field-based, like Colombia, but with greater reliance on heaps and pits for processing residues, resulting in a mixed N_2O-CH_4 emission profile.

In all origins, Z-score analysis confirms that residue-related emissions are not driven by a small number of extreme cases but reflect consistent management practices across farms. Collectively, these findings indicate that residue management represents a key mitigation lever across coffee supply chains, with priority actions differing by country: optimization of field-based residue handling in Brazil Arabica and Colombia, consolidation and expansion of aerobic composting in Peru, structural shifts away from anaerobic handling in Honduras, and incremental improvements in processing-residue management in Mexico.

Several methodological limitations should be made explicit when interpreting the residue results presented and generated with the CFP tool. First, allometric and age-based biomass functions are inherently sensitive to context. In CFP, coffee systems are represented without further differentiation by species (e.g. Coffea Arabica versus

Coffea Robusta), despite the fact that these species may exhibit different growth patterns and biomass allometries. In addition, CFP represents all coffee trees within a farm as belonging to a single, uniform age cohort. In practice, coffee plantations typically consist of a heterogeneous population of trees of varying ages due to staggered planting, selective replanting, and mortality. When trees are replaced, CFP assumes the new trees have the same age as the rest of the plantation, whereas in reality, newly planted trees contribute substantially less biomass. This simplification can influence the estimated amounts of standing biomass and the volume of biomass entering residue pools in the assessment year. More generally, allometric approaches rely on statistical generalization across observed systems and therefore embed structural uncertainty when extrapolated to highly heterogeneous production contexts. Reducing this source of uncertainty would require coffee-specific, site- and system-level studies that develop species- and management-sensitive allometric relationships (Ketterings et al., 2001)[21].

Second, yield-based estimation of residues (scaling residues to harvested output) implicitly assumes relatively stable residue-to-yield relationships. In the CFP methodology, for example, a fixed conversion factor of 0.5647 is applied to represent the proportion of coffee fruit mass that becomes husk or pulp. In coffee, yield can fluctuate strongly (biennial bearing, climate stress, pests), while pruning, litterfall, mortality, and management decisions may not fluctuate proportionally. This can lead to under- or over-estimation of certain residue pools in anomalously low or high yield years, particularly when residue generation is driven by structural biomass dynamics (age, renovation, shade management) rather than by harvest alone (Ledo et al., 2018)[22].

For the management pathways, the percentage allocation of residues depends on self-reported practice shares and assumes proportional splitting adequately represents real-world handling. In practice, residue management can be episodic (e.g., occasional burning events), spatially heterogeneous (different plots or slopes), and temporally clustered (processing season), so percentage inputs may smooth peaks in anaerobic conditions or misrepresent the duration of storage in heaps or pits, both of which are important for CH_4 formation.

These limitations do not invalidate the approach used in this study, but they od imply that residue results should be interpreted as best-estimate, management-sensitive indicators rather than precise measurements. Improving farm data on pruning frequency, mortality, residue moisture handling, and the share and time residues

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[21] Ketterings, Q. M., Coe, R., Van Noordwijk, M., Ambagau', Y., & Palm, C. A. (2001). Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. Forest Ecology and Management, 146(1-3), 199-209. https://doi.org/10.1016/S0378-1127(00)00460-6

[22] Ledo, A., Heathcote, R., Hastings, A., Smith, P., & Hillier, J. (2018). Perennial-GHG: A new generic allometric model to estimate biomass accumulation and greenhouse gas emissions in perennial food and bioenergy crops. Environmental Modeling and Software, 102, 292-305. https://doi.org/10.1016/j.envsoft.2017.12.005

spend in heaps or pits would directly improve the robustness of CFP-based residue baselines for coffee.

Future studies could strengthen the basis for estimating residue-related emission by improving methodological alignment and expanding empirical data collection. Harmonized allometric functions that distinguish between coffee species, cultivars, and management systems would reduce uncertainty in biomass estimation, while more detailed farm-level information on pruning frequency, mortality, residue moisture handling, and storage duration would enhance the accuracy of residue-flow modelling. In addition, refining residue-to-yield conversion factors through targeted field measurements, rather than relying on fixed coefficients would better capture a year-to-year variability in production systems. The development of standardized reporting formats and guidance for characterizing residue management pathways (e.g., composting, piling, pit storage, burning frequency) would further support comparability across studies.

Collectively, such improvements would contribute to a stronger methodological foundation for future assessments in the coffee sector.

5.5. WASTEWATER

5.5.1. OVERVIEW

In CFP, GHG emissions from wastewater are estimated following the IPCC 2019 Guidelines for National GHG Inventories, with emissions attributed exclusively to CH_4 generated during wastewater treatment. The methodology links the volume of wastewater produced during coffee processing to its organic load, expressed through chemical oxygen demand (COD) or biochemical oxygen demand (BOD), which serve as proxies for the degradable organic matter available for methane formation. Emissions are calculated by combining wastewater volumes (reported by farms), organic content expressed as COD or BOD, and a methane conversion factor that reflects the treatment pathway and degree of anaerobic conditions. For coffee processing, CFP recommends using a default COD value of 9,000 mg per liter, consistent with IPCC guidance for coffee wastewater, which was used for the majority of farms assessed in this study in the absence of site-specific measurements. This approach ensures conservative and consistent estimation of wastewater-related emissions up to farm-gate across countries, while allowing variability in results to be driven primarily by differences in processing intensity and treatment practices rather than by assumed organic load values.
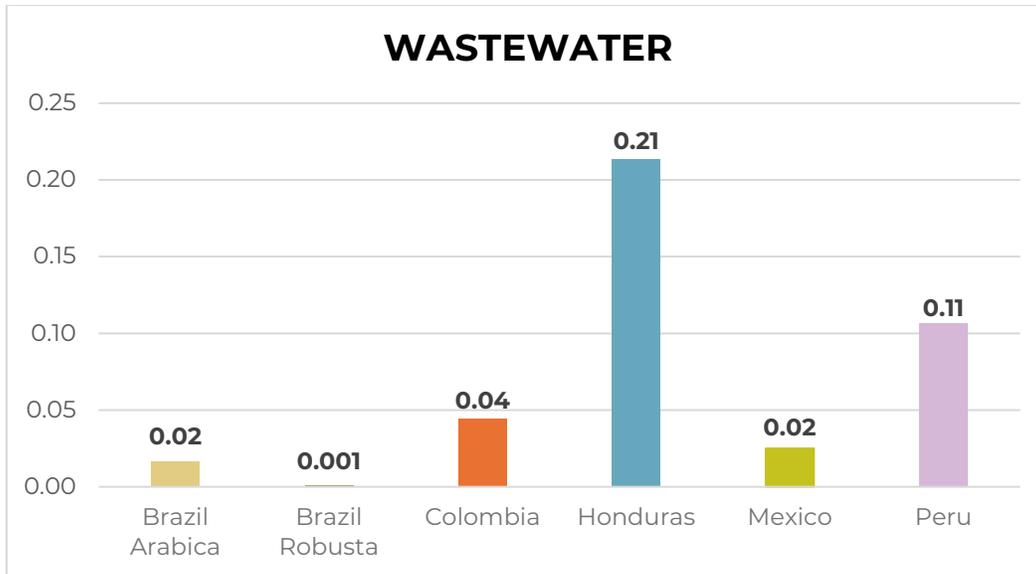
Figure 34: Breakdown of wastewater emissions by countries

5.5.2.   RESULTS FOR BRAZIL ARABICA

In the Brazilian Arabica coffee supply chain up to farm-gate, emissions from wastewater treatment represent a negligible contribution to the overall on-farm carbon footprint. Total wastewater-related emissions amount to 1,634,437.46 kg CO_2-eq, corresponding to 0.02 kg CO_2-eq per kg GBE and accounting for approximately 0.02% of total farm-gate emissions.

These results confirm that wastewater emissions play only a marginal role in shaping aggregate carbon footprint outcomes for Brazilian Arabica production, when maintaining farm-gate as the boundary.

A total of 129 farms disclosed that they conduct on-farm coffee processing, indicating that on-farm wet processing is present but not universal within the Brazilian Arabica system. Among these farms, wastewater treatment practices show substantial heterogeneity. Sludge anaerobic digestion systems are the most frequently reported treatment option (65 farms), followed by anaerobic lagoons (24 farms). Constructed wetlands with vertical subsurface flow are reported by 17 farms, while surface flow constructed wetlands are used by 6 farms. The remaining farms rely on stagnant sewer or unmanaged systems.

Z-score analysis indicates that wastewater-related emissions are concentrated within a limited subset of farms, with 27 farms exhibiting per-ha wastewater emissions above the mean. These elevated values reflect farm-specific treatment configurations or higher wastewater volumes, mostly exhibited by the farms utilizing anaerobic lagoons. However, given the very low absolute contribution of wastewater emissions given the farm-gate boundary, this variability does not materially influence national farm-gate-level carbon footprint estimates.

Overall, the marginal contribution of on-farm wastewater emissions in Brazilian Arabica production reflects the limited prevalence of farm-specific wet processing, the predominance of low- to moderate-intensity treatment systems on-farms, and relatively small resulting wastewater volumes. While farm-level heterogeneity in wastewater management is evident, wastewater treatment remains a minor emission source within a farm-gate boundary, compared with fertilizer use, crop residue management, and energy-related emissions.

5.5.3. RESULTS FOR BRAZIL ROBUSTA

In the Brazilian Robusta coffee supply chain up to farm-gate, emissions from wastewater treatment represent a negligible contribution to the overall farm-gate carbon footprint. Total wastewater-related emissions amount to 42,167.97 kg CO_2-eq, corresponding to 0.001 kg CO_2-eq per kg GBE and accounting for approximately 0.03% of total farm-gate emissions.

This confirms that wastewater emissions play a very limited role in shaping aggregate emission results for Brazilian Robusta production when considering farm-gate as the boundary.

Wastewater generation is reported by 53 farms, indicating that only a relatively small subset of producers conducts on-farm washing. Among these farms, wastewater treatment practices vary. Vertical subsurface flow constructed wetlands are the most frequently reported treatment option, used by 26 farms, followed by sludge anaerobic digestion systems, reported by 22 farms. A very small number of farms rely on centralized aerobic treatment plants, reported by 2 farms, while the remaining systems include simple anaerobic lagoon configurations. This diversity of treatment

pathways reflects heterogeneity in infrastructure and management practices rather than systematic differences in production intensity.

Z-score analysis indicates that wastewater-related emissions are highly concentrated within a small number of farms. When emissions are analyzed both per ha and per kg GBE, 4 of the 53 farms conducting on-farm washing exhibit Z-scores greater than 2, with the same farms identified across both normalization approaches. This indicates structurally higher wastewater-related emissions for a limited subset of producers. However, given the very low absolute contribution of wastewater emissions within the boundary, this variability does not materially influence national farm-gate-level carbon footprint results.

Overall, the negligible contribution of on-farm wastewater emissions in Brazilian Robusta production reflects the limited prevalence of on-farm wet processing, the use of low-intensity treatment systems, and the relatively small volumes of wastewater generated. While farm-level heterogeneity is evident, particularly among a small number of farms, wastewater treatment remains a minor emission source within the farm-gate boundary in comparison with fertilizer use, crop residue management, and fuel and energy consumption.

5.5.4. RESULTS FOR COLOMBIA

In Colombia, wastewater treatment contributes a small but clearly identifiable share of the total farm-gate coffee carbon footprint. Total on-farm wastewater-related emissions are estimated at 210,024.13 kg CO_2-eq, equivalent to 0.04 kg CO_2-eq per kg GBE and representing approximately 0.8% of total farm-gate emissions. These emissions are driven primarily by treatment system characteristics rather than by absolute wastewater volumes.

Among farms reporting on-farm wet processing, wastewater treatment practices are highly heterogeneous. The most frequently reported systems are constructed wetlands with vertical subsurface flow (160 farms), followed by centralized aerobic treatment plants (69 farms) and anaerobic reactors (67 farms). Sludge anaerobic digestion systems are reported by 60 farms, while horizontal subsurface flow constructed wetlands account for 33 farms and surface flow wetlands for 2 farms. A smaller number of farms report anaerobic lagoons, both deeper than 2 m (6 farms)

and shallower than 2 m (3 farms). In addition, several farms report no formal treatment, discharging wastewater to unspecified aquatic environments (50 farms), fast-flowing sewers (51 farms), stagnant sewers (6 farms), or other unmanaged outlets (13 farms).

Z-score analysis indicates that wastewater-related emissions are concentrated within a limited subset of farms, with 20 out of 600 farms exhibiting elevated total wastewater emissions, 17 farms on a per-ha basis, and 9 farms on a yield-normalized basis. In all cases, the affected farms represent a statistically negligible share of the sample, and elevated values are not consistently observed across normalization approaches.

Overall, wastewater treatment remains a minor contributor to the Colombian farm-gate coffee carbon footprint when compared with structurally dominant emission sources such as crop residue management and fertilizer use. While substantial farm-level heterogeneity in wastewater management systems exists, this variability does not materially influence national farm-gate carbon footprint results.

5.5.5. RESULTS FOR HONDURAS

In contrast to Brazil and Colombia, wastewater treatment plays a more substantial role in the Honduran coffee supply chain. Total wastewater-related emissions are estimated at 1,065,668.93 kg CO_2-eq, corresponding to 0.21 kg CO_2-eq per kg GBE and accounting for approximately 4.3% of total farm-gate emissions.

This higher contribution reflects both a greater prevalence of wet processing and the nature of wastewater treatment systems, many of which create conditions conducive to methane formation.

Wastewater treatment practices in Honduras are highly heterogeneous, with a strong predominance of anaerobic systems. Sludge anaerobic digestion systems are the most frequently reported treatment option (129 farms), followed by constructed wetlands with vertical subsurface flow (107 farms). Anaerobic lagoons are also widely used, including deep lagoons (>2 m; 73 farms) and shallow lagoons (<2 m; 56 farms). A smaller number of farms report horizontal subsurface flow constructed wetlands (13 farms), centralized aerobic treatment plants (8 farms), anaerobic reactors (1 farm), or surface flow wetlands (1 farm). Very few farms report unmanaged discharge pathways, such as stagnant sewers (1 farm), fast-flowing sewers (2 farms), or discharge to reservoirs, lakes, or estuaries (1 farm).

Z-score analysis highlights substantial farm-level variability, with 55 farms exhibiting per-ha wastewater emissions above the mean, underscoring the influence of treatment configuration and management practices. Average wastewater generation reaches 10,924.99 liters per ha, emphasizing the importance of water-intensive processing steps in shaping emission outcomes.

Overall, while wastewater emissions do not dominate the Honduran farm-gate coffee carbon footprint, they represent a meaningful and structurally important emission source relative to other origins. The combination of high wet-processing prevalence, anaerobic treatment pathways, and elevated wastewater volumes positions wastewater management as a clear mitigation opportunity within the Honduran coffee sector.

5.5.6. RESULTS FOR MEXICO

In the Mexican coffee supply chain, wastewater emissions remain a minor but non-negligible contributor to overall farm-gate emissions. Total wastewater-related emissions amount to 109,736.58 kg CO_2-eq, corresponding to 0.02 kg CO_2-eq per kg GBE and representing approximately 1.7% of total farm-gate emissions.

While wastewater emissions do not materially influence aggregate national results, they are sufficiently pronounced to warrant consideration in specific processing contexts.

Wastewater treatment practices in Mexico are highly heterogeneous, with a strong predominance of nature-based and anaerobic systems. Sludge anaerobic digestion systems are the most frequently reported treatment option (170 farms), followed by constructed wetlands with vertical subsurface flow (153 farms). Additional systems include horizontal subsurface flow constructed wetlands (15 farms), anaerobic lagoons deeper than 2 m (8 farms), shallow anaerobic lagoons (<2 m; 2 farms), surface flow wetlands (1 farm), and centralized aerobic treatment plants (1 farm). A smaller subset of farms report unmanaged discharge pathways, including fast-flowing sewers (20 farms) and stagnant sewers (3 farms), while no discharges to reservoirs, lakes, or estuaries are reported.

Z-score analysis identifies 65 farms with per-ha wastewater emissions above the mean, highlighting variability in processing intensity and treatment efficiency across farms. Average wastewater generation reaches 5,539.53 liters per ha, substantially lower than observed in Honduras, helping to explain the comparatively smaller contribution of wastewater emissions to the Mexican coffee footprint.

Overall, wastewater emissions in Mexico, when considering the farm-gate boundary, remain secondary relative to dominant sources such as fertilizer use and crop residue management. However, the combination of heterogeneous treatment systems and localized emission hotspots indicates that processing-stage interventions could deliver targeted mitigation benefits in specific segments of the Mexican coffee supply chain.

5.5.7. RESULTS FOR PERU

In the Peruvian coffee supply chain, emissions from wastewater treatment make a moderate contribution to the overall farm-gate carbon footprint. Total wastewater-related emissions amount to 259,968.06 kg CO_2-eq, corresponding to 0.11 kg CO_2-eq per kg GBE and representing approximately 4% of total farm-gate emissions.

Compared to Brazil and Colombia, wastewater therefore plays a more visible role in Peru, although it remains secondary to structurally dominant sources such as crop residue management.

Wastewater treatment practices in Peru are highly heterogeneous, with a strong predominance of anaerobic systems. Anaerobic lagoons deeper than 2 m are the most frequently reported treatment option (177 farms), followed by sludge anaerobic digestion systems (155 farms). Anaerobic reactors are also widely used (86 farms), while constructed wetlands with vertical subsurface flow are reported by 85 farms. Additional systems include horizontal subsurface flow constructed wetlands (19 farms), shallow anaerobic lagoons (<2 m; 19 farms), and centralized aerobic treatment plants (9 farms). A small number of farms report unmanaged discharge pathways, including stagnant sewers (10 farms) and fast-flowing sewers (1 farm).

Z-score analysis identifies 27 farms with per-ha wastewater emissions above the mean, indicating variability in treatment technologies and processing intensity across farms.

However, the limited proportion of farms exhibiting elevated values confirms that wastewater emissions do not compromise the statistical representativeness of the national results.

Overall, wastewater emissions in Peru represent a meaningful but non-dominant emission source when considering the farm-gate boundary. The combination of widespread on-farm wet processing and the prevalence of anaerobic treatment systems highlight wastewater management as a relevant mitigation opportunity, particularly when compared with origins where wastewater plays only a marginal role.

5.5.8. CONCLUSIONS AND LIMITATIONS

Across the five coffee-producing countries assessed, wastewater-related emissions up to the farm-gate show substantial cross-country variability driven not only by treatment practices but also by the prevalence of on-farm wet processing. While wastewater emissions within the boundary remain negligible in Brazil and Colombia, they become increasingly relevant in Honduras, Peru, and Mexico. This variation in emission intensity is partly explained by differences in wastewater treatment pathways but is also strongly influenced by the number of farms carrying out on-farm washing and fermentation. In Brazil and Colombia, only a relatively small share of farms undertakes on-farm wet processing, which dilutes the contribution of wastewater emissions when aggregated at the supply-chain level. In contrast, a much larger proportion of farms in Honduras and Mexico perform on-farm processing, leading to higher on-farm wastewater volumes and a more pronounced contribution of CH_4 emissions from treatment. As a result, wastewater emerges as a structurally minor emission source in Brazil and Colombia, but a more material contributor in Honduras and Peru, and to a lesser extent in Mexico. These findings highlight that wastewater emissions are highly sensitive to processing farms within the supply chain and underscore the importance of targeting mitigation measures specifically at farms engaged in wet processing, rather than applying uniform interventions across all producers.

Several methodological limitations should be made explicit when interpreting the wastewater results. These limitations primarily relate to the characterization of wastewater organic content, the representation of treatment pathways, and the practical constraints associated with farm-level data collection across diverse coffee-producing regions.

First, GHG emissions from wastewater in CFP are estimated following the IPCC 2019 Guidelines for National GHG Inventories, which attribute emissions exclusively to CH_4 generated during anaerobic degradation of organic matter in wastewater systems

(IPCC, 2019[23]). Emissions are calculated as a function of wastewater volume, organic content expressed as COD or BOD, and a methane conversion factor (MCF) reflecting the degree of anaerobic conditions. While this approach is consistent with international reporting standards, it relies on simplified representations of complex biological and operational processes occurring during coffee processing and wastewater treatment.

A key limitation arises from the use of standardized COD or BOD values in the absence of site-specific measurements. COD and BOD values in coffee wastewater are typically derived from laboratory analyses of composite samples collected during the processing season and are known to vary substantially depending on processing method (e.g., fully washed, semi-washed), pulp-to-water ratios, fermentation practices, dilution, and the timing and frequency of sampling (Madu et al., 2019; Metcalf & Eddy, 2014)[24] [25]. Reported COD values for coffee wastewater in the literature span a wide range, reflecting both temporal variability within a season and spatial variability across mills and regions. The CFP-recommended default COD value of 9,000 mg per liter, consistent with IPCC guidance, provides a pragmatic and conservative proxy in data-scarce contexts, but may mask local variability and lead to under- or overestimation of CH_4 emissions at the individual farm level.

Second, the representation of wastewater treatment pathways in CFP necessarily simplifies real-world management practices. Methane emissions are strongly influenced by factors such as retention time, oxygen availability, temperature, sludge accumulation, and episodic discharge events, which are often not systematically recorded at the farm (or mill) level (IPCC, 2019; Hailemariam et al., 2021)[26]. In practice, coffee wastewater management can be highly heterogeneous, with treatment systems ranging from open lagoons and pits to partial reuse or uncontrolled discharge and may vary within a single processing season. The use of fixed or categorical MCFs, therefore, represents an abstraction of these dynamics and introduces additional uncertainty into emission estimates.

Third, wastewater generation and treatment are inherently seasonal and temporally clustered around the harvest period. Annualized assessments, as required for consistency with GHG frameworks, implicitly smooth short-term peaks in organic loading and anaerobic conditions that may drive episodic CH_4 emissions (GHG

[23] IPCC (2019). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5: Waste.

[24] Madu, Ijanu & Kamaruddin, Mohamad & Norashiddin, Faris Aiman. (2019). Coffee processing wastewater treatment: a critical review on current treatment technologies with a proposed alternative. Applied Water Science. 10. 11. 10.1007/s13201-019-1091-9.

[25] Metcalf & Eddy (2014) Wastewater Engineering: Treatment and Resource Recovery. 5th Edition, McGraw-Hill, New York.

[26] Hailemariam, Fitsum & P, Velmurugan & Selvaraj, Senthil. (2021). Treatment of wastewater from coffee (coffea arabica) industries using mixed culture Pseudomonas florescence and Escherichia coli bacteria.

Protocol, 2011; IPCC, 2019) [27] [28]. As a result, annual emission estimates should be interpreted as average representations of wastewater-related emissions over the reporting year, rather than as precise reflections of peak emission events during processing.

Taken together, these limitations highlight that wastewater-related emission estimates generated using CFP are most robust when interpreted at aggregated scales (e.g., national or system-level baselines), where variability in organic load and management practices is partially averaged out. At finer spatial scales, results should be interpreted with caution and primarily used for comparative or screening purposes rather than precise farm-level accounting.

The study acknowledges these limitations and emphasizes the need for greater methodological alignment and improved data availability in future assessments. Priority areas for improvement include the development of harmonized sampling and measurement protocols for COD/BOD in coffee wastewater, guidance on representative sampling frequency and timing during the processing season, and the collection of regionally representative wastewater characterization data. Where feasible, targeted measurement campaigns at representative processing farms could support the derivation of context-specific COD/BOD ranges and more refined MCF assumptions, enabling progression toward higher-tier methodologies consistent with IPCC Tier 2 or Tier 3 approaches. Such advancements would strengthen the accuracy of wastewater emission estimates and enhance their utility for mitigation planning and long-term climate strategy development within the coffee sector.

5.6. TRANSPORTATION

5.6.1. OVERVIEW

In CFP, transport-related GHG emissions are estimated based on the movement of coffee and associated materials within and just past the farm boundary, including transport from farms to collection points, mills, or first buyers. Emissions are calculated as a function of the transported mass, the distance travelled, and the transport mode used. CFP applies default, mode-specific emission factors expressed per ton per kilometer, which account for vehicle type and fuel use and include well-to-tank emissions. These emission factors are derived from authoritative sources, including DESNZ and DEFRA, ensuring consistency with internationally recognized LCA practices. Where farm-specific fuel consumption data are unavailable, this distance-

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[27] GHG Protocol, 2011
[28] IPCC, 2019

and mass-based approach provides a transparent and conservative estimate of transport emissions. Variability in transport emissions across farms, therefore, reflects differences in transported volumes, yields, distances, and logistics structures, rather than assumptions embedded in the methodology itself.
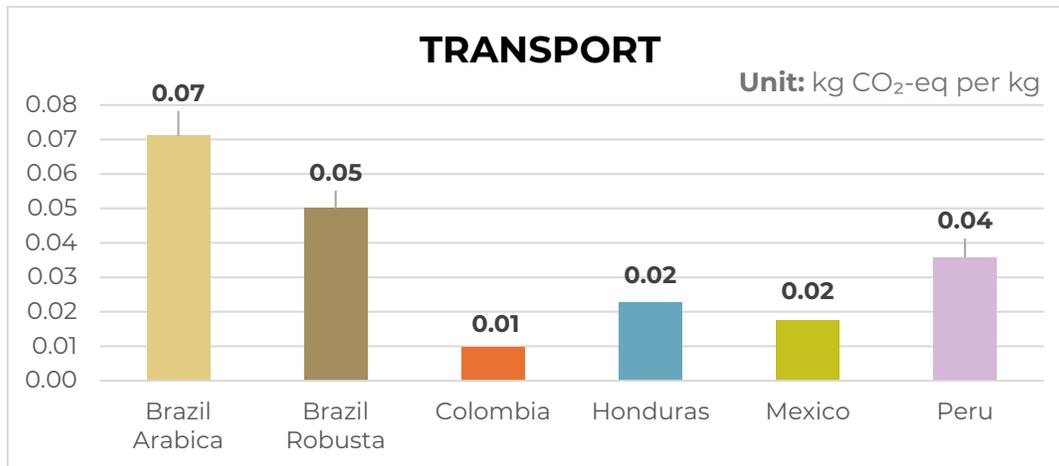
Figure 35: Breakdown of transport emissions by countries

5.6.2.   RESULTS FOR BRAZIL ARABICA

In the Brazilian Arabica supply chain, transportation plays a slightly more visible, though still secondary, role in the overall farm-gate carbon footprint. Total transportation emissions are estimated at 7,130,750.51 kg CO_2-eq, equivalent to 0.07 kg CO_2-eq per kg GBE and accounting for approximately 2.2% of total emissions.

Z-score analysis identifies 36 farms with transport emissions above the mean on an area basis, while normalization by yield reduces this number to 18 farms. These results reflect heterogeneity in transport distances and yield across farms, but confirm that transportation remains a structurally minor emission source compared to dominant on-farm processes such as fertilizer use and residue management.

5.6.3. RESULTS FOR BRAZIL ROBUSTA

In the Brazilian Robusta coffee supply chain, transportation represents a secondary emission source at the farm-gate. Total transport-related emissions amount to 2,673,687.63 kg CO_2-eq, corresponding to 0.05 kg CO_2-eq per kg GBE and accounting for approximately 2.17% of total farm-gate emissions. Transportation therefore plays a limited role compared to dominant on-farm emission sources such as fertilizer use and crop residue management.

Z-score analysis shows moderate variability in transport emissions, with eight farms exhibiting values above the mean when emissions are assessed both per ha and per kg GBE, although different farms are identified under each normalization. This reflects heterogeneity in transport distances rather than the influence of a small group of structurally high-emission farms. Transport is dominated by road-based diesel vehicles, primarily heavy goods vehicles, with average incoming and outgoing distances of 88 km and 40 km, respectively. Farms with elevated transport emissions are characterized by substantially longer distances, confirming that transport-related emissions are primarily driven by logistical factors rather than systemic inefficiencies.

5.6.4. RESULTS FOR COLOMBIA

In the Colombian coffee supply chain, emissions from transportation are negligible relative to other emission sources within the farm-gate. Total transportation emissions amount to 45,928.72 kg CO_2-eq, corresponding to 0.01 kg CO_2-eq per kg GBE and representing approximately 0.2% of total farm-gate emissions.

Z-score analysis indicates that 24 farms exhibit transport emissions above the mean when expressed on an area basis, representing around 4% of the sample. However, when emissions are normalized by production (kg GBE), only a single farm shows an exceptionally high Z-score. This case is attributable to an extremely low reported yield, which disproportionately inflates transport emissions per unit of output. Overall,

transportation emissions within the farm-gate boundary in Colombia remain marginal and do not influence the representativeness of the dataset or the interpretation of key emission drivers.

5.6.5.   RESULTS FOR HONDURAS

In Honduras, transportation emissions play a very limited role in the overall carbon footprint. Total emissions from transport amount to 113,608.56 kg CO_2-eq, equivalent to 0.02 kg CO_2-eq per kg GBE and representing approximately 0.5% of total farm-gate emissions.

Z-score analysis identifies 5 farms with transport emissions above the mean on an area basis, while 9 farms exhibit elevated Z-scores when normalized by yield. One farm shows an exceptionally high Z-score, driven by a combination of low transported volume and high dead-tree counts, which distorts the emission intensity metric. Excluding this case does not materially alter aggregated results, confirming that transportation emissions in Honduras within the farm-gate boundary remain marginal.

5.6.6.   RESULTS FOR MEXICO

In the Mexican coffee supply chain, transportation emissions remain a minor contributor to overall emissions. Total transport-related emissions amount to 76,382.45 kg CO_2-eq, corresponding to 0.017 kg CO_2-eq per kg GBE and representing approximately 1.2% of total farm-gate emissions.

Z-score analysis identifies 6 farms with elevated transport emissions, primarily driven by long downstream transport distances, averaging around 192 km. While these cases highlight the influence of logistics configuration on farm-level transport emissions, their limited number ensures that transportation does not significantly affect the aggregate footprint.

5.6.7. RESULTS FOR PERU

In the Peruvian coffee supply chain, emissions from transportation remain limited. Total transport-related emissions amount to 87,314.01 kg CO_2-eq, corresponding to 0.04 kg CO_2-eq per kg GBE and representing approximately 1.3% of total farm-gate emissions.

Z-score analysis identifies 28 farms with transport emissions above the mean on an area basis, equivalent to around 5% of the sample, while yield-normalized analysis shows 31 farms with elevated Z-scores. This reflects moderate variability in transport intensity and distances but does not materially affect the overall emission profile. Transportation therefore remains a secondary contributor within the Peruvian coffee footprint, considering the farm-gate boundary.

5.6.8. CONCLUSION

Across all five countries, transportation consistently represents a secondary emission source, contributing less than 3% of total farm-gate emissions in all cases. Variability in transport emission intensity is driven primarily by differences in yield levels, transport distances, and supply-chain aggregation structures rather than by systematic differences in production systems. Countries with more centralized collection and processing systems, such as Colombia and Brazil, show diluted transport emissions when aggregated at a supply-chain level, while longer downstream distances or lower yields can lead to elevated transport intensities for individual farms, as observed in Mexico and selected cases in Peru and Honduras. Overall, the results confirm that while transport optimization may offer incremental efficiency gains, transportation is not a primary mitigation lever in coffee supply chains when compared to on-farm emission sources such as fertilizer use, residue management, and wastewater treatment.

6. UNCERTAINTY ASSESSMENT

6.1. OVERVIEW

An uncertainty assessment is a critical component of a carbon footprint analysis, as it enables transparent interpretation of results and provides context for understanding the reliability of estimated emissions. All results presented in this study should

therefore be interpreted as indicative estimates rather than exact values, reflecting inherent variability in agricultural systems and limitations in data availability and modeling approaches. All carbon footprint estimates in this assessment are furthermore subject to uncertainty arising from multiple sources, including:

- Sampling errors associated with using a subset of farms to represent a larger population;
- Model-related assumptions embedded in the CFP (and the 4C Carbon tool applied for comparative analysis in Section 9);
- Accuracy of farmer-reported data;
- Data gaps or missing information requiring the use of default values.

Consistent with the approach adopted in the USAID GIA study, the uncertainty assessment presented here focuses primarily on sampling uncertainty, expressed as variability and margins of error derived from the sample. Other sources of uncertainty are acknowledged and discussed qualitatively but are not quantitatively incorporated into the margin of error.

It should be noted that the calculated Margin of Error (MoE) reflects only random sampling uncertainty. Systematic biases, such as consistent underreporting or misreporting of inputs, are not captured in the MoE and therefore are not reflected in the final emission values used for the assessments.

Further, as the baseline assessment is based on data collected for a single full harvesting season, additional uncertainty arises from year-to-year variability in coffee yields, fertilizer use, and climatic conditions. Given the perennial nature of coffee production, future assessments could reduce uncertainty by incorporating data from multiple coffee calendar years to better capture temporal variability. Further industry alignment around such an approach is recommended.

6.2. SAMPLING VARIABILITY

Sampling variability arises from heterogeneity in farm-level practices, yields, and input use within and across countries. Differences in fertilizer application rates, residue management practices, wastewater treatment methods, and transport distances contribute to variability across the sampled farms. Sample sizes differed across districts and countries, which affects the precision of aggregated estimates. Although the sampling strategy aimed to capture a representative range of production systems and practices, some uncertainty remains regarding how fully the sample reflects the underlying population. A Z-score analysis was therefore applied across multiple emission categories to identify extreme values and assess the representativeness of the datasets. Across all countries and categories, the proportion of extreme outliers

was limited, supporting the robustness of the sampling approach and the reliability of aggregated results.

6.3. DATA COLLECTION AND REPORTING UNCERTAINTY

Several challenges encountered during data collection affected the accuracy of reported information. Many smallholder farmers lacked systematic record-keeping practices, making it difficult to accurately recall certain activities, such as the types and quantities of fertilizers applied. Although enumerators provided support during interviews, some degree of recall-related uncertainty remains. Similar challenges were observed for pesticide use, where farmers often relied on approximations rather than precise records.

Transportation data for inputs and coffee within farms were also frequently based on estimates or proxy values rather than direct measurements, introducing additional uncertainty into transport-related emission calculations. These issues reflect structural limitations in data availability within smallholder coffee systems rather than isolated reporting errors.

For wastewater treatment, when farmers were unable to report BOD or COD values, a default concentration of 9,000 mg/L was applied. While this ensures consistency across calculations, the use of a default value may underestimate actual emissions in cases where wastewater strength is higher than assumed.

6.4. MODEL-RELATED UNCERTAINTY

Model-related uncertainty is primarily associated with the structure and assumptions of the CFP. Limitations include the simplified categorization of crop residue management practices by percentage, which may not fully capture the diversity of on-farm residue treatment pathways. During data collection and quality control, some ambiguity arose in the classification of aerobic versus anaerobic residue treatment practices. Although enumerators were trained on these distinctions, the final classification relied on enumerators' on-site vetting and verification of farmer-reported practices, based on observable management conditions and contextual information collected during farm visits.

Additional model-related uncertainty arises from the absence of verified information on fertilizer manufacturing origin, which necessitated the use of default values based on the most common fertilizer availability in each country. Similarly, transportation modeling options within the tools are constrained, limiting differentiation between certain transport modes or logistics pathways.

Where farm-specific data points were missing or incomplete, default emission factors and assumptions embedded in the tools were applied. While this enhances consistency and comparability across farms and countries, it introduces additional uncertainty at the individual farm level.

6.5. MARGIN OF ERROR CALCULATION

To quantify sampling uncertainty associated with the carbon footprint estimates, MoE was calculated for each country at a 95% confidence level. This reflects uncertainty arising from sampling variability only and is intended to indicate the statistical precision of the estimated mean carbon footprint values. The calculation used followed standard statistical approaches for estimating confidence intervals from sample data and is consistent with the methodology applied in comparable carbon footprint assessments[29].

As mentioned, the farm samples used in this study were selected using a stratified sampling approach, where strata were defined at sub-national levels (e.g., districts or regions), and sample sizes were allocated proportionally to production volumes. As a result, the aggregated sample for each country already reflects the production-weighted structure of the underlying population. Because this weighting is embedded in the sampling design itself, no additional weighting factors were applied during the MoE calculation. Applying weights again at this stage would have constituted double weighting and would have distorted the estimation of sampling uncertainty. Therefore, the MoE was calculated directly from the observed variability within the final weighted sample.

MoE formula

For each country, the MoE[30] was calculated using the standard formula for the mean of a sample:

$$MoE = SE \times z_\alpha$$

$$SE = \frac{s}{\sqrt{n}}$$

where:

- z_α is the z-score corresponding to a 95% confidence level (1.96),
- SE is the Standard Error,
- s is the sample standard deviation of the carbon footprint indicator (kg CO_2-eq per kg GBE),

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[29] Walpole, R. E., Myers, R. H., Myers, S. L., & Ye, K. (2012). Probability and statistics for engineers and scientists (9th ed.). Pearson.
[30] Triola, M. F. (2018). Elementary statistics (13th ed.). Pearson

- n is the effective sample size.

The MoE and confidence intervals at the national level are provided in Table 22 below.

COUNTRY	MEAN (KG CO$_2$-EQ PER KG GBE)	N	COEFFICIENT OF VARIANCE (%)	MARGIN OF ERROR (KG CO$_2$-EQ PER KG GBE)	MARGIN OF ERROR (%)	95% CONFIDENCE INTERVAL
Brazil Arabica	3.34	500	68.5%	$\pm$ 0.23	7%	[2.98,3.46]
Brazil Robusta	2.73	371	52.1%	$\pm$ 0.15	5%	[2.07,2.98]
Colombia	5.78	600	56.8%	$\pm$ 0.37	7%	[5.22,5.96]
Honduras	5.02	601	59.2%	$\pm$ 0.32	7%	[4.54,5.18]
Mexico	1.68	605	75.3%	$\pm$ 0.28	20%	[1.17,1.74]
Peru	2.89	620	60.1%	$\pm$ 0.26	9%	[2.58,3.10]

Table 22: MoE for CFP results

To ensure that the MoE reflects sampling variability rather than the influence of extreme observations, farms with Z-scores exceeding 2 were excluded from the MoE calculation (check Section 4.1.2 for Z-score analysis). These farms were analyzed separately as part of an outlier assessment. This approach is consistent with the objective of estimating uncertainty around the mean for most of the farms and avoids distortion of confidence intervals due to a small number of atypical observations.

The significantly higher MoE observed for Mexico can be partly attributed to data quality constraints. Compared with other countries, the Mexican dataset exhibited greater uncertainty in key farm-level input variables, reflecting extensive reliance on farmer recall and limited availability of verifiable records for specific management practices. As minor inconsistencies in reported inputs can lead to greater dispersion around the mean, this increases the standard error and, consequently, the MoE. In addition, Mexico's lower average emission intensity amplifies the relative MoE when expressed as a percentage, even when absolute uncertainty remains comparable to that of other countries.

7. CARBON CAPTURED BY NON-CROP ESTIMATED BIOMASS

Coffee production systems, particularly perennial systems, are inherently diverse and frequently extend beyond monocultural cropping. Intercrops, shade trees, and hedges are integral components of many coffee farms and can substantially influence the farm-level GHG balance.

Although these non-crop elements are typically associated with carbon sequestration through the accumulation of above-ground biomass, it is important to emphasize that the values presented in this report do not yet represent sequestration. At this stage, the data reflect only the baseline estimated biomass, which serves as an initial stock assessment prior to modeling any sequestration over time.

Non-crop components contribute to system productivity and resilience income streams, while also regulating microclimatic conditions and protecting soils. In addition, they play a key role in agroecological functioning by enhancing nutrient cycling, reducing erosion, and supporting on-farm biodiversity. Excluding such co-products from the system boundary would therefore underestimate the carbon storage potential of coffee production systems and result in an incomplete representation of farm-gate emissions and potential removals. For this reason, non-crop plants, specifically intercrops, shade trees, and hedges, are included in the assessment wherever data availability and methodological coverage allow.

During primary data collection, farmers were asked to report the presence of co-products on their farms using an extensive predefined list of species (Annex 2). This approach was applied consistently across all countries, enabling farmers to select species that most accurately reflected their on-farm conditions. Consequently, the dataset captures a broad diversity of non-crop species, reflecting the structural baseline of on-farm vegetation rather than sequestration outcomes. For each country, information was collected on the type of non-crop vegetation (intercrop, shade tree, or hedge), the species present, and key structural parameters, including plant density, the percentage of farm area occupied, and the average age of trees. These parameters establish the baseline of non-crop biomass against which future sequestration may be modeled.

The CFP methodology to estimate biomass changes in non-crop vegetation focuses on (1) selected intercrop species, (2) generic shade tree categories, such as tropical trees in wet or dry areas, and canopy or understory classes, and (3) hedges based on species-specific or mixed parameters. However, CFP offers only a limited number of predefined species and generic categories to choose from for intercrops—namely, rubber, avocado, durian, jackfruit, and cashew—as well as shade trees (inclusive of

tropical shade trees and temperate conifers), and shrubs. As a result, several species reported by farmers could not be directly mapped to available CPF categories and were therefore excluded from the non-crop biomass calculation. The carbon capture estimate for non-crop plants is thus conservative and does not fully reflect the diversity of species reported during data collection. This limitation arises from the availability of model parameters rather than from gaps in the primary data. In light of this, it is important to note that estimates of carbon stored in non-crop biomass may underestimate total on-farm carbon stocks, particularly in highly diversified agroforestry systems.

COUNTRY	NON-CROP BIOMASS, ESTIMATED (KG CO$_2$-EQ)	NON-CROP BIOMASS, ESTIMATED (KG CO$_2$-EQ PER HA)	NON-CROP BIOMASS, ESTIMATED (KG CO$_2$-EQ PER KG GBE)
Brazil Arabica	-147457.05	-3.43	-0.001417
Brazil Robusta	-6937009.8	-445.51	-0,140971
Colombia	-1592450.3	-435.92	-0.337435
Honduras	-937969.09	-290.52	-0.187948
Mexico	-304330.73	-198.56	-0.069319
Peru	-450338.96	-263.36	-0.184734

Table 23: Non-crop biomass estimates according to CFP by country

In summary, the values reported here represent only the baseline stock of non-crop woody biomass and do not yet constitute removals as defined under the LSRG GHGP. Because ongoing measurements, growth modeling, and geospatial verification are not available within this study, these estimates cannot be used to report sequestration or offset emissions. They establish an initial reference point from which future changes may be tracked. Strengthening species-specific parameters, improving periodic data collection, and integrating remote-sensing tools will be essential steps to enable more complete and LSRG-aligned removals reporting in subsequent cycles.

8. FACTOR-SPECIFIC ANALYSIS

8.1. OVERVIEW

The factor-specific analysis applied in this section is conceptually distinct from the archetype framework used during the sampling design. In the sampling phase, archetypes were defined across seven varying factors to ensure that the dataset adequately reflected heterogeneity within national production systems. The primary

objective of that approach was to safeguard representativeness and enable robust national-level comparisons.

In contrast, the factor-specific analysis presented here concentrates exclusively on variables that demonstrably influence farm-gate GHG emissions across countries. Relevant factors for analysis were created if they had the following characteristics:

- Clearly related to emission levels,
- Reflective of farmer decisions or farm characteristics that could be easily understood, and
- Related to enough data points to allow reliable comparisons.

Factors that did not meet these criteria were excluded to avoid overly complex groupings, weak conclusions, or the highlighting of practices that were not truly meaningful in relation to GHG emissions. If farms were grouped using factors that had little impact on emissions, the resulting groups may have differed on paper, but not in actual emission outcomes, which could make results harder to interpret and increase uncertainty.

Within this framework, two key factors were established: **fertilizer application intensity** and **certification status**. Fertilizer use is a decision made by farmers and is directly linked to major emission sources. It also varies enough across farms to support meaningful comparisons. Certification status, meanwhile, reflects a broader farm characteristic that is highly relevant to stakeholders, and helps describe differences in practices among farms.

Farm size was considered among the factors but was ultimately excluded as a main factor for analysis. Although some data related to farm size is provided in the tables below, and there were enough small farms in the dataset, there were too few medium and large farms in several countries to support reliable comparisons. This resulted in unstable estimates regarding farm size's impact on emissions, and large uncertainty. In addition, definitions of small, medium, and large farms vary widely across countries and production systems; applying a single set of size thresholds would reduce comparability and weaken the validity of the analysis.

While yield is related to emission intensity, it reflects the combined result of many interacting factors such as management practices, environmental conditions, and past decisions, rather than a single action under a farmer's control. As such, yield was not used as a primary grouping variable within the factor-specific analysis. Instead, the yield values are presented alongside fertilizer application intensity groups in tables below to contextualize emission outcomes across fertilizer-use categories, without implying a direct or uniform relationship between productivity and input intensity.

While the below analysis of **fertilizer application intensity** and **certification status** within this section aligns with the methodology used in the USAID GIA study, it is

important to note that grouping farms based on total fertilizer applied per ha does not fully capture differences in nitrogen input. Mineral fertilizers vary widely in nitrogen content and emission profiles; for example, urea differs significantly from compound NPK fertilizers. As such, grouping farms only by the total mass of fertilizer applied hides important differences in nitrogen-related emissions.

A more detailed approach would require defining fertilizer categories in advance, based on agreed industry criteria for distinguishing fertilizers with different emission impacts. Such an approach would also require country-specific analysis of fertilizer use patterns to ensure that categories are meaningful, and enough farms would need to be included for reliable comparisons. As this level of detail was beyond the scope of the current study, the results analyzing fertilizer-based groups should be interpreted as general indicators of management intensity, rather than precise measures of nitrogen use and its impact. Future studies could improve accuracy by accounting for differences in fertilizer composition and nitrogen content when defining farm groupings, using available data. Conducting an archetype analysis based on those that were previously established to define the heterogeneity of systems is further recommended and was specifically highlighted by the study's third-party reviewer.

8.2. FERTILIZER APPLICATION INTENSITY

Before classifying farms into fertilizer-use groups, the dataset was screened to identify unusually high fertilizer application rates that could distort the results. A Z-score analysis was used to flag extreme values. Farms with exceptionally high application rates were treated as outliers and excluded from the analysis to ensure that the resulting groups reflected typical farming practices rather than rare extremes.

The number of fertilizer-use groups was chosen to balance clarity with statistical reliability, and different options were tested. A two-group system was tested but considered too broad as it masked meaningful differences in fertilizer use and emissions. Systems with more than three groups resulted in categories with too few farms, making results unreliable and difficult to interpret. A three-group system—**low, medium, and high fertilizer use**—provided the best balance, as it preserved enough detail to show meaningful differences while ensuring reliable comparisons across countries. This approach was furthermore consistent with USAID GIA, which reached a similar conclusion.

The thresholds separating the low, medium, and high fertilizer-use groups were determined using a data-driven method called **Jenks natural breaks**. This method identifies natural groupings in the data by placing boundaries where differences between farms are largest, and where similarities within groups are strongest. Using this approach avoids arbitrary cut-off points and ensures that farms are grouped in a way that reflects real patterns in fertilizer use. Once again, it also maintains consistency with USAID GIA.

Below is the breakdown by country:

COUNTRY	LOW INPUT THRESHOLD (KG/HA)	MEDIUM INPUT THRESHOLD (KG/HA)	HIGH INPUT THRESHOLD (KG/HA)
BRAZIL ARABICA	< 800	800-2000	>2000
BRAZIL ROBUSTA	< 1100	1100-3000	>3000
COLOMBIA	< 900	900-2000	>2000
HONDURAS	< 800	800-2000	>2000
MEXICO	< 800	800-1800	>1800
PERU	< 630	630-1850	>1850

Table 24: Threshold for fertilizer input use by countries

Analyses based on input intensity

BRAZIL ARABICA	Low input threshold	Medium input threshold	High input threshold
Percentage of farms	26%	33%	41%
Median yield (kg/ha)	1810.05	1729.22	1800.00
Average yield (kg/ha)	2304.69	2127.36	2146.46
Average coffee plot size (ha)	49.82	71.77	117.75
Average emissions (kg CO_2-eq per kg GBE)	1.45	2.96	3.53

Table 25: Analyses based on input threshold - Brazil Arabica

BRAZIL ROBUSTA	Low input threshold	Medium input threshold	High input threshold
Percentage of farms	69%	27%	4%
Median yield (kg/ha)	3130.43	3165.22	3225.0
Average yield (kg/ha)	3244.06	3172.24	3294.09
Average coffee plot size (ha)	42.83	63.94	14.60
Average emissions (kg CO_2-eq per kg GBE)	2.60	2.12	2.44

Table 26: Analyses based on input threshold - Brazil Robusta

COLOMBIA	Low input threshold	Medium input threshold	High input threshold
Percentage of farms	26%	57%	17%
Median yield (kg/ha)	769.23	1076.92	1091.09
Average yield (kg/ha)	1109.32	1557.04	1500.28
Average coffee plot size (ha)	5.38	7.32	9.13
Average emissions (kg CO_2-eq per kg GBE)	5.50	5.54	7.45*

*Note: The high-input threshold represents a very small share of the sample (17% of farms) and is characterized by disproportionately high emission intensities. These values are driven by a limited number of high-input farms rather than by a systematic shift in the production system, and therefore primarily reflect heterogeneity in fertilizer application practices within Colombia. As a result, results for the high-input category should be interpreted with caution and should not be taken as representative of typical national production conditions.

Table 27: Analyses based on input threshold - Colombia

HONDURAS	Low input threshold	Medium input threshold	High input threshold
Percentage of farms	67%	30%	3%
Median yield (kg/ha)	959.84	1020.83	1057.69
Average yield (kg/ha)	1503.02	1735.74	2385.64
Average coffee plot size (ha)	4.88	5.53	5.77
Average emissions (kg CO_2-eq per kg GBE)	3.92	5.04	7.25*

*Note: The high-input threshold represents a very small share of the sample (3% of farms) and is characterized by disproportionately high emission intensities. These values are driven by a limited number of high-input farms rather than by a systematic shift in the production system, and therefore primarily reflect heterogeneity in fertilizer application practices within Honduras. As a result, results for the high-input category should be interpreted with caution and should not be taken as representative of typical national production conditions.

Table 28: Analyses based on input threshold - Honduras

MEXICO	Low input threshold	Medium input threshold	High input threshold
% of farm	69%	25%	6%
Median yield (kg/ha)	761.53	1047.11	1692.30
Average yield (kg/ha)	886.50	1144.88	1282.17
Average coffee plot size (ha)	2.37	2.58	4.09
Average emissions (kg CO_2-eq per kg GBE)	1.19	1.31	2.05*

Table 29: Analyses based on input threshold - Mexico

PERU	Low input threshold	Medium input threshold	High input threshold
Percentage of farms	66%	28%	6%
Median yield (kg/ha)	777.05	1245.53	1478.40
Average yield (kg/ha)	1164.93	1861.83	2023.57
Average coffee plot size (ha)	2.95	2.92	3.12
Average emissions (kg CO_2-eq per kg GBE)	2.89	2.84	2.64

Table 30: Analyses based on input threshold - Peru

As the above results show that fertilizer use, yield, and GHG emissions are not correlated in the same way across countries and categories (e.g., higher input use does not always translate to higher yields, and lower input use does not always translate to reduced emissions).

To further assess how these three variables relate to one another, three statistical measures were used: **correlation**, **explained variance (R^2)**, and the **fertilizer–yield slope**. These measures help describe how strongly variables are related, how much they help explain differences in emissions, and how yields tend to respond to fertilizer use. While they are used to describe patterns in the data, they do not imply cause-and-effect relationships.

- **Correlation** shows whether two variables tend to increase or decrease together. For example, it can indicate whether higher fertilizer-related emissions are associated with higher total farm emissions, or whether higher yields are linked to higher or lower emissions. Correlation helps identify relationships but does not prove that one factor causes another. Regardless, it may support farmer decision-making.

- **Explained variance (R^2)** shows how much of the difference in emission intensity across farms can be accounted for by a single factor, such as fertilizer-related emissions or yield. A higher R^2 value means that the factor helps explain a larger share of the observed variation between farms.

- The **fertilizer–yield slope** describes how yields change, on average, as fertilizer use increases. It provides an indication of how responsive yields are to additional fertilizer within the observed range of data; differences around this average

relationship reflect variations in farm management, environmental conditions, and production efficiency. For easier interpretation, fertilizer–yield responsiveness is grouped into three categories:

- o **Low responsiveness (elasticity below 0.2):** Yields change very little as fertilizer use increases;
- o **Medium responsiveness (0.2–0.5):** Yields respond somewhat to fertilizer, but results vary across farms;
- o **High responsiveness (above 0.5):** Yields increase strongly with additional fertilizer.

Together, these three measures help identify which factors are most useful for understanding emission patterns. They also help explain differences observed between countries.

Fertilizer application intensity is a primary driver of farm-gate GHG emissions across most studied countries, typically accounting for approximately 48% to 61% of the total carbon footprint up to farm-gate3, with the notable exception of Peru, where fertilizer contributes only 18%. Using a data-driven three-group classification (low, medium, and high input), the results further show that higher fertilizer intensity generally corresponds with higher emission intensity. However, increased input levels do not consistently translate into proportional productivity gains. In Brazil (Arabica and Robusta), for example, yield responsiveness is low, indicating that yields remain relatively stable despite increasing fertilizer inputs. Moreover, in Brazil Arabica and Colombia, average yields decline beyond an observed inflection point of approximately 2,290 kg (Figure 36) and 2,071 kg (Figure 37) of fertilizer per ha, respectively, suggesting diminishing or negative marginal returns at higher application rates within the observed data range.

Meanwhile, in Colombia, Honduras, and Mexico, the high-input categories represent only a small share of farms (approximately 3% to 17%) yet exhibit disproportionately high emission intensities, indicating that these outcomes reflect specific management extremes rather than broader national production patterns. Overall, the findings still highlight fertilizer management as a key emission lever, while underscoring the non-linear and context-dependent nature of its relationship with productivity.

Mitigation implications from the analysis suggests prioritizing nutrient-management strategies that improve nitrogen-use efficiency and reduce avoidable fertilizer-related emissions (e.g., better timing, and placement; avoiding over-application; and improving overall agronomic efficiency), alongside broader on-farm efficiency measures where feasible. However, these are general, data-informed indications rather than prescriptive interventions; real-world mitigation outcomes depend heavily

on local biophysical conditions, farmer objectives, institutional support, and economic feasibility (costs, labor, risk, access to inputs and advisory services), and may differ substantially even between neighboring farms.

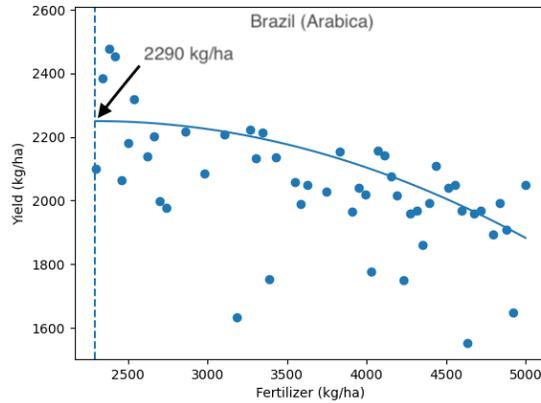| COUNTRY	FERTILIZER EMISSION SHARE IN TOTAL FOOTPRINT	CORRELATION	R^2	FERTILIZER–YIELD SLOPE (E)
BRAZIL ARABICA	59%	0.67	0.41	Low
BRAZIL ROBUSTA	61%	0.73	0.51	Low
COLOMBIA	60%	0.62	0.38	Medium
HONDURAS	48%	0.57	0.30	Medium
MEXICO	48%	0.35	0.25	Medium
PERU	18%	0.29	0.21	Low

Table 31: Fertilizer-yield relationship
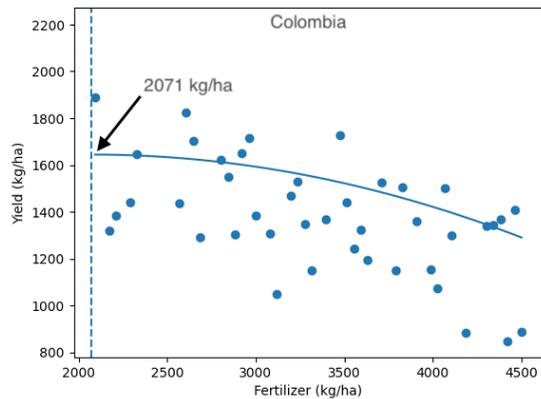

Figure 36: Inflection point - Brazil (Arabica)

Figure 37: Inflection point - Colombia

8.3. CERTIFICATION STATUS

Certification status is frequently discussed as a potential pathway for improving environmental performance in coffee production because certification schemes may be associated with expert agronomic guidance, improved record keeping, and participation in structured support programs that can influence management practices (Franzen & Borgerhoff Mulder, 2007[31]; Blackman & Naranjo, 2012[32]). However, certification itself does not constitute a direct management input, and certification schemes differ widely in their objectives, requirements, and enforcement, such that observing differences between certified and non-certified farms does not imply that certification per se causes those differences (Rice et al., 2015[33]; DeFries et al., 2017[34]). In recognition of these methodological constraints and based on multiple partner feedback, certification is treated in this study as a descriptive attribute rather than as an explanatory variable for emission outcomes.

An exploratory comparison was conducted to examine whether certified and non-certified farms exhibit different distributions of farm-gate carbon footprint intensity (kg CO_2-eq per kg GBE) within the available dataset. This analysis was not designed to evaluate the impact or effectiveness of certification schemes, nor to attribute differences in emission intensity to certification status. Rather, it is intended to describe observable associations in the context of the baseline dataset. Farms were classified into two categories—certified and non-certified based on self-reported certification status at the time of data collection—as scheme-level information was not consistently available. The results in Table 32 are presented solely as contextual associations and not as indicators of certification performance or mitigation effectiveness. The analysis does not control for confounding variables or isolate the independent influence of certification or its specifically recommended practices, and it therefore does not support causal inference (Blackman & Naranjo, 2012[35]; McDermott, 2013[36]). A more robust assessment of the impacts of certification on farm-gate GHG

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[31] Franzen, M., & Borgerhoff Mulder, M. (2007). Ecological, economic and social perspectives on cocoa production worldwide. Biodiversity and Conservation, 16(13), 3835–3849. https://doi.org/10.1007/s10531-007-9183-5
[32] Blackman, A., & Naranjo, M. A. (2012). Does eco-certification have environmental benefits? Organic coffee in Costa Rica. Ecological Economics, 83, 58–66. https://doi.org/10.1016/j.ecolecon.2012.08.001
[33] Irwandi, Putra & Hasibuan, M. & Syah Putra, Hendris. (2025). THE IMPACT OF COFFEE FARMER CERTIFICATION ON FARMING SUSTAINABILITY (Bibliometric and Content Analysis). 10. 602-617. 10.37149/JIMDP.v10i6.2456.
[34] DeFries, R. S., Fanzo, J., Mondal, P., Remans, R., & Wood, S. A. (2017). Is voluntary certification of tropical agricultural commodities achieving sustainability goals for small-scale producers? Environmental Research Letters, 12(3), 033001.10.1088/1748-9
[35] Blackman, A., & Naranjo, M. A. (2012). Does eco-certification have environmental benefits? Organic coffee in Costa Rica. Ecological Economics, 83, 58–66. https://doi.org/10.1016/j.ecolecon.2012.08.001
[36] McDermott, 2013

emissions would be useful, but would require a dedicated study design that (1) incorporates improved scheme differentiation, and practice differentiation by scheme into the data collection framework; (2) integrates certification criteria into the sampling framework; (3) and controls for key confounders such as farm size, fertilizer use, and production context. Such designs, including matched comparisons or longitudinal evaluations, have been advocated in sustainability impact literature and are necessary to distinguish scheme effects from other managerial and structural variables (Jena et al., 2012[37]; DeFries et al., 2017[38]). Certification is therefore identified as an important but methodologically complex dimension that warrants targeted investigation in future research, rather than as a variable that can be meaningfully interpreted within this baseline dataset.

COUNTRY	CERTIFICATION STATUS	% OF FARMS	AVERAGE CARBON FOOTPRINT CFP (KG CO$_2$-EQ PER KG GBE)
BRAZIL ARABICA	Certified	52%	2.89
	Non-certified	48%	3.29
BRAZIL ROBUSTA	Certified	64%	2.55
	Non-certified	36%	2.43
COLOMBIA	Certified	65%	5.89
	Non-certified	35%	5.32
HONDURAS	Certified	60%	4.55
	Non-certified	40%	5.19
MEXICO	Certified	60%	1.21
	Non-certified	40%	1.98
PERU	Certified	90%	2.99
	Non-certified	10%	2.13

Table 32: Analysis of carbon footprint according to certification status

9.   COMPARATIVE ANALYSIS

9.1. 4C CARBON FOOTPRINT ADD-ON

The 4C Carbon Footprint Add-On, developed by 4C Services GmbH, enables farmers, cooperatives, and production companies to calculate and manage GHG emissions across certified coffee supply chains using a rigorous, science-based methodology. It relies on primary data, defines clear system boundaries from farm to export (with

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[37] Jena, P. R., Stellmacher, T., & Grote, U. (2012). The impact of coffee certification on small-scale producers' livelihoods: A case study from the Jimma Zone, Ethiopia. *Agricultural Economics, 43*(4), 429–440.https://doi.org/10.1111/j.1574-0862.2012.00594.

[38] DeFries, R. S., Fanzo, J., Mondal, P., Remans, R., & Wood, S. A. (2017). Is voluntary certification of tropical agricultural commodities achieving sustainability goals for small-scale producers? Environmental Research Letters, 12(3), 033001.10.1088/1748-9

optional inclusion of final buyers), and ensures full traceability through digital integration in the 4C Portal. The 4C tool aligns with internationally recognized standards, including ISO 14067, the GHGP, PAS 2050, SBTi, and IPCC guidelines. The following results employ the same sampling framework and database as the CFP analysis to facilitate comparison. Each section highlights country-specific differences and similarities identified through the comparative analysis. The following Table 33 provides a cross-country summary of the final results generated by the 4C and CFP methodologies, after which the subsequent paragraphs present, interpret, and analyze the detailed category-level breakdowns.

COUNTRY	CFP Methodology (KG CO$_2$-EQ PER KG GBE)	4C Methodology (KG CO$_2$-EQ PER KG GBE)
BRAZIL ARABICA	3.22	2.67
BRAZIL ROBUSTA	2.51	1.91
COLOMBIA	5.59	5.43
HONDURAS	4.87	4.07
MEXICO	1.46	1.25
PERU	2.84	1.81

Table 33:Cross-country summary of the final results from both methodologies

9.1.1. BRAZIL ARABICA

The 4C tool estimated an average carbon footprint of **2.67 kg CO$_2$-eq per kg GBE** for the Brazilian Arabica supply chain up to farm-gate. Fertilizer use is the largest contributor, accounting for 1.81 kg CO$_2$-eq per kg GBE (68% of total emissions) and equaling 3,917 kg CO$_2$-eq per ha. This closely mirrors CFP results and indicates strong consistency in identifying farms with elevated fertilizer-related emissions in order to target mitigation. As both the CFP and the 4C methodologies apply the same IPCC framework for estimating direct and indirect soil N$_2$O emissions from fertilizer application, differences between tools therefore arise from fertilizer-specific production emission factors, nitrogen content, soil characteristics, and default volatilization/leaching fractions.

As with CFP, crop residues represent the second largest source of emissions when applying the 4C tool, contributing 0.53 kg CO$_2$-eq per kg GBE (20% of total emissions), followed by machinery operations at 0.04 kg CO$_2$-eq per kg GBE (1.5% of total emissions). While the three greatest sources of emissions are aligned under both

methodologies, emissions from crop residue management under the 4C tool are considerably lower than CFP, with totals of 49,642,261.43 kg CO_2-eq, corresponding to 1,154.82 kg CO_2-eq per ha. The observed differences are driven by methodological choices in biomass estimation and emission calculation. Specifically, when farm-level data on residue quantities are unavailable, CFP estimates biomass using age-based equations or yield-based curves that dynamically link residue production to crop productivity and plant characteristics, typically yielding higher and more variable residue availability. By contrast, the 4C tool relies on fixed literature-derived values that represent average conditions and are less sensitive to farm-level variability in yield, plant age, or management intensity. Consequently, residue quantities and emissions are generally lower under 4C. These estimation differences combined with distinct emission factors and decay assumptions, explain the divergence in residue-related emissions between the methodologies, and provide further justification for the need for increased industry alignment around residue management. All remaining categories play minor roles, similar to the results obtained using CFP.

SOURCE	CFP (kg CO_2-eq per GBE)	4C (kg CO_2-eq per GBE)
Fertilizer use	1.9	1.81
Crop residues	1.09	0.53
Machinery operations	0.09	0.04
Transport	0.07	0.03
Fuel & energy	0.03	0.03
Wastewater	0.02	0.002
Irrigation	0.002	0
Pesticides	0.001	0.02
Total	**3.22**	**2.67**

Table 34: Comparative emission breakdown: Brazil - Arabica

9.1.2. BRAZIL ROBUSTA

The 4C tool estimated an average carbon footprint of **1.91 kg CO_2-eq per kg GBE** for the Brazilian Robusta supply chain up to farm-gate. Fertilizer use is the largest contributor, accounting for 1.19 kg CO_2-eq per kg GBE (approximately 62% of total farm-gate emissions), corresponding to 3,815.52 kg CO_2-eq per ha. This result is consistent with CFP findings for Brazilian Robusta and confirms mineral fertilizer management as the dominant driver of emission intensity. Also consistent with CFP, crop residues represent the second largest emission source under 4C, contributing 0.49 kg CO_2-eq per kg GBE (approximately 26% of total emissions), equivalent to 1,638.55 kg CO_2-eq per ha. As with Brazil Arabica, residue-related emissions estimated under the 4C tool are lower than those obtained using CFP, once again reflecting methodological differences in biomass estimation and emission calculation.

Irrigation energy contributes 0.10 kg CO_2-eq per kg as the third-highest emitter under the 4C tool, which is equal to the emissions under CFP; irrigation was also the third-highest emitter in the case of CFP. When applying the 4C tool, fuel and energy use contribute 0.06 kg CO_2-eq per kg GBE, and machinery operations contribute 0.03 kg CO_2-eq per kg GBE, making these secondary but non-negligible contributions, which reflect mechanization and energy requirements in Brazilian Robusta production systems. Transport, pesticides, wastewater, and non-crop biomass account for only minor shares of total emissions. Overall, fertilizer use and crop residue management clearly emerge as the principal emission hotspots for Brazilian Robusta production up to farm-gate, under both the 4C and the CFP.

Source	CFP (kg CO_2-eq per GBE)	4C (kg CO_2-eq per GBE)
Fertilizer use	1.53	1.19
Crop residues	0.69	0.49
Machinery operations	0.08	0.04
Transport	0.05	0.03
Fuel & energy	0.05	0.06
Wastewater	0.001	0.0005
Irrigation	0.10	0.10
Pesticides	0.004	0.01
Total:	**2.51**	**1.91**

Table 35: Comparative emission breakdown: Brazil - Robusta

9.1.3. COLOMBIA

The 4C tool estimates an average footprint of **5.43 kg CO_2-eq per kg GBE** for the Colombian supply chain up to farm-gate. The predominant contributor is fertilizer use, at 3.23 kg CO_2-eq per kg GBE (59% of total emissions). Total emissions from fertilizer production across the Colombian supply chain amount to 7,569,611.32 kg CO_2-eq, and on-field emissions across the 600 farms assessed equal 7,607,166.13 kg CO_2-eq, indicating a roughly even split; this supports the conclusion that both methodologies employ similar approaches for fertilizer-related emissions, as explained previously.

The second-largest source of emissions is crop residues under 4C, contributing 1.72 kg CO_2-eq per kg GBE (32% of total emissions). However, while the top two categories of emissions are the same under both methodologies, 4C estimates for crop residues are approximately 5% lower than CFP. Both tools consistently identify pruning and dead-plant residues as key intervention points for mitigation, however, and the close alignment between relative contributions and residue-type rankings confirms strong methodological consistency. The small divergence in totals is driven by the same process-level modeling differences explained above.

Wastewater emissions are slightly higher under 4C, totaling 328,904.95 kg CO_2-eq, equivalent to 0.07 kg CO_2-eq per kg GBE and 90.04 kg CO_2-eq per ha. This difference makes wastewater the third-highest emitter under 4C (distinct from CFP, where machinery was the third-highest emitter) and originates from the emission factors used for wastewater treatment. It is primarily attributable to variations in methane correction factors and default wastewater treatment assumptions. In particular, the option to record wastewater or effluent that is discharged directly onto soil is not available under CFP, requiring enumerators to choose the closest available alternatives—such as discharge into fast-flowing sewer systems or into unspecified aquatic environments—based on what they observed in the field, which affects methane emission estimates.

Finally, transport emissions amount to 74,630.63 kg CO_2-eq, or 0.02 kg CO_2-eq per kg GBE (0.3% of overall emissions) under the 4C tool. Upstream transport accounts for 44.28% of transport emissions (33,048.19 kg CO_2-eq) and downstream contributes 55.72% (41,583.45 kg CO_2-eq). While not one of the top three sources of emissions in either case, both CFP and 4C confirm transportation as a minor contributor in Colombia; specific differences reflect scope and emission-factor assumptions, while overall patterns and outlier shares remain consistent.

Source	CFP (kg CO_2-eq per GBE)	4C (kg CO_2-eq per GBE)
Fertilizer use	3.35	3.23
Crop residues	1.82	1.72
Machinery operations	0.30	0.36
Transport	0.01	0.02
Fuel & energy	0.07	0.02
Wastewater	0.04	0.07
Irrigation	0	-
Pesticides	0.001	0.01
Total:	5.59	5.43

Table 36: Comparative emission breakdown: Colombia

9.1.4.   HONDURAS

The 4C tool estimates an average carbon footprint of **4.07 kg CO_2-eq per kg GBE** for Honduras up to farm-gate. Crop residue management is the largest contributor, at 1.99 kg CO_2-eq per kg GBE (49% of total emissions), with total emissions of 9,941,212.35 kg CO_2-eq (equaling 3,079.15 kg CO_2-eq per ha). It should be emphasized that this outcome differs from the CFP approach, where the largest contributor is fertilizer. However, the discrepancy is negligible in terms of aggregated values and its proportional contribution to overall GHG results.

Fertilizer use is the second largest source of emissions under 4C, at 1.97 kg CO_2-eq per kg GBE (≈48% of the total emissions) and 2,936 kg CO_2-eq per ha. As mentioned, this also contrasts with the CFP results, where the second-highest contributor is residue management. The difference in crop residues and fertilizers primarily reflects methodological and modeling assumptions embedded within each tool, particularly how residue decomposition, emission factors, and nitrogen-related emissions are parameterized, rather than a fundamental divergence in farm-level activity data or overall emission magnitude.

Overall, CFP and 4C results present a consistent and credible picture of both fertilizer and crop residue related emissions in the Honduran coffee supply chain. Despite methodological differences for these categories, both approaches identify crop residue management and fertilizer use as the principal emission hotspots within the Honduran coffee supply chain up to farm gate. This is relevant for mitigation purposes, and confirms categorical impact. All other emission categories play only a minor role in the overall footprint under both tools, with machinery operations being the third largest category in both.

Source	CFP (kg CO_2-eq per GBE)	4C (kg CO_2-eq per GBE)
Fertilizer use	2.33	1.97
Crop residues	2.00	1.99
Machinery operations	0.25	0.05
Transport	0.02	0.02
Fuel & energy	0.03	0.02
Wastewater	0.21	0.01
Irrigation	0	0
Pesticides	0.008	0.006
Total	4.87	4.07

Table 37: Comparative emission breakdown: Honduras

9.1.5. MEXICO

The 4C tool estimates an average carbon footprint of **1.25 kg CO_2-eq per kg GBE** for Mexico up to farm-gate. Fertilizer use is identified as the largest contributor, accounting for 0.61 kg CO_2-eq per kg GBE (49% of total emissions), equivalent to 1,751 kg CO_2-eq per ha. Taken together, the CFP and 4C methodologies present a coherent and internally consistent picture of fertilizer-related emissions in the Mexican coffee supply chain. Both methodologies identify fertilizer use as the primary source of emissions up to farm-gate, even when application rates are relatively low.

Similarly, crop residues represent the second largest source, under both tools, with 4C identifying contributions of 0.58 kg CO_2-eq per kg GBE (46% of total emissions). Under

4C, emissions from crop residue management are marginally higher, reaching 2,555,220.91 kg CO_2-eq, equivalent to 1,667.19 kg CO_2-eq per ha in comparison to CFP.

Another difference comes up in the fuel and energy emissions category, which contributes 0.03 kg CO_2-eq per kg GBE (2% of total emissions) under the 4C tool, totaling 113,618.45 kg CO_2-eq. This is a slightly higher share than CFP, making it the third largest category under 4C, while under CFP, the third-highest contributor was machinery operations. This discrepancy can be attributed to the difference in emission factors used between the tools. Regardless, the use of biomass and fossil fuels for energy activities contributes only marginally at the farm level, with emissions of 6,301.59 kg CO_2-eq, accounting for 5.5% of the total emissions within this category under 4C. Overall, fuel and energy are still minor contributors in Mexico under both tool, although interestingly distinct from other countries in that this category appears among the top drivers in Mexico's emission profile up to farm-gate.

Source	CFP (kg CO_2-eq per GBE)	4C (kg CO_2-eq per GBE)
Fertilizer use	0.69	0.61
Crop residues	0.58	0.58
Machinery operations	0.12	0.02
Transport	0.02	0.007
Fuel & energy	0.02	0.02
Wastewater	0.02	0.002
Irrigation	0	0
Pesticides	0.0003	0.001
Total	**1.46**	**1.25**

Table 38: Comparative emission breakdown: Mexico

9.1.6.   PERU

For Peru, the 4C tool estimates an average footprint of **1.81 kg CO_2-eq per kg GBE** up to farm-gate. As with CFP, crop residues are the dominant contributor, at 1.07 kg CO_2-eq per kg GBE (59% of total emissions). Emissions under 4C total 2,614,450.94 kg CO_2-eq, corresponding to 1,528.99 kg CO_2-eq per ha. Most emissions originate from dead-plant treatment (70%), followed by pruning waste (22%) and coffee pulp/husk (8%), with no major differences relative to CFP.

Fertilizer use is the second largest source, at 0.44 kg CO_2-eq per kg GBE (24% of the total emissions), equivalent to 622.75 kg CO_2-eq per ha. This once again aligns with CFP, with total emissions from fertilizer production amounting to 833,042.24 kg CO_2-eq under 4C, which is very low compared with other national baselines assessed in this study. On-field emissions across the 620 farms produced a total of 231,807.13 kg CO_2-eq.

Taken together, CFP and 4C results provide a clear and internally consistent picture of the impact of both crop residues and fertilizer use in Peru, even as the third largest contributor differed under the two methodologies. Under CFP, the third-largest contributor to emissions is machine operations, while under 4C, it is wastewater. This variation reflects differences in modeling assumptions rather than contradictions in the underlying farm data. Specifically, the tools apply different assumptions regarding fuel consumption and emission factors for treatment pathways.

Source	CFP (kg CO_2-eq per GBE)	4C (kg CO_2-eq per GBE)
Fertilizer use	0.51	0.44
Crop residues	1.89	1.07
Machinery operations	0.28	0.07
Transport	0.04	0.03
Fuel & energy	0.02	0.02
Wastewater	0.11	0.18
Irrigation	0	0
Pesticides	0.0008	0.003
Total:	**2.84**	**1.81**

Table 39: Comparative emission breakdown: Peru

10. LESSONS LEARNED AND RECOMMENDATIONS

10.1. INTRODUCTION

This study represents one of the most comprehensive efforts to date to establish statistically robust, farm-gate carbon footprint baselines for coffee production across major Latin American origins. Conducted as a pre-competitive collaboration initiative involving roasters, traders, sustainability organizations, and technical partners, the study demonstrates the value of cross-sector cooperation in generating shared evidence to support climate action in the coffee sector. By combining large-scale primary data collection, a heterogeneity-informed sampling framework, comparative analysis across multiple carbon accounting frameworks, and explicit uncertainty assessment, the study provides both empirical insights into dominant emission drivers and practical lessons regarding current methodological and operational constraints.

Importantly, the collaborative structure of the study enabled partners across the coffee value chain to align on common approaches for data collection, system boundaries, and emission estimation, helping to strengthen transparency and comparability of results across different producing contexts. While the results presented reflect conditions observed during a single production year, they provide a robust evidence base for benchmarking farm-gate emissions and identifying priority mitigation areas within coffee production systems.

At the same time, the findings establish a strong foundation for future work. The dataset, methodological insights, and lessons learned from implementation provide a basis for refining data collection practices, improving modelling assumptions, and expanding analysis across additional years and geographies. Building on this baseline through continued collaboration will be essential for improving the precision of carbon footprint estimates and supporting the design of more targeted, context-appropriate mitigation strategies across the coffee sector.

One central lesson is that variability in reported carbon footprints is driven not only by differences in farm practices, but also by ex-ante design choices related to survey structure, parameter definitions, modeling assumptions, and tool capabilities. As a result, several of the most influential emission sources observed in this study, particularly fertilizer nitrogen inputs and crop residue management, require improved pre-competitive alignment across the industry—among roasters, retailers as well as civil society—surrounding objectives, data collection, and analytical scope at a study design stage to ensure that in future iterations of similar work, final results are increasingly comparative within the sector. The recommendations below, therefore, relate to both data collection practices and methodological design, and focus on how the coffee sector can strengthen the interpretability, robustness, and future usability of coffee carbon footprint baselines.

10.2. RECOMMENDATIONS FOR DATA COLLECTION AND SURVEY DESIGN

Several lessons emerged from the implementation and quality-control phases of the data collection process. First, survey timing proved to be a critical determinant of data quality. Enumerators consistently reported higher confidence in farmers' recall of input quantities, application timing, and post-harvest practices when interviews were conducted close to harvest. Future baseline updates should therefore align survey deployment with harvest calendars and avoid extended recall periods, particularly for parameters directly influencing emission calculations. While the iterative quality-control process highlighted the value of strong enumerator training, validation protocols, and feedback loops, it also exposed the limits of farmer recall for technically

complex parameters. Where feasible, future studies should complement survey responses with farm records, cooperative-level data, or digital input tracking systems to reduce reliance on recall-based reporting.

Second, although the study delivers statistically robust national baselines, single-year assessments inherently limit interpretation. Annualized carbon footprints are suitable and required for corporate GHG accounting and benchmarking but do not capture interannual variability driven by climate conditions, biennial bearing, or changing management intensity. Future studies should therefore prioritize multi-year replication to distinguish structural mitigation progress from year-specific fluctuations. To acknowledge and mitigate for interannual variability, for some data points (e.g. yields and inputs) 'past year' data was collected to allow for comparison.

Third, the study highlights the need to balance methodological rigor with operational feasibility. Practical constraints including survey length, enumerator capacity, coordination across origins, budget limitations, and reliance on Supplier Partners for farm access required adjustments during implementation. Although a randomization protocol was defined, full random farm selection was not always achievable because farm access was mediated through participating supply chains. Consequently, the dataset should be interpreted as representative of participating supply chains rather than national farming populations. Compared to USAID GIA, these operational realities also resulted in smaller sample sizes across countries, illustrating the trade-offs inherent in large-scale multi-country primary data collection.

At the same time, larger and more targeted sample sizes would improve the ability to assess management practices such as agroforestry, residue management, and wastewater treatment in a statistically robust manner, particularly where variability is high or practices are underrepresented. Where full randomization is not possible, future studies could strengthen robustness through hybrid approaches such as independent farm registries to define sampling frames, two-stage stratified sampling, post-sampling weighting, or sensitivity analyses. Clear documentation of these constraints will improve transparency and comparability of future baseline assessments.

Given these realities, concentrating future data-collection efforts on the most influential emission categories—fertilizer use, crop residue management, and wastewater treatment—offers a pragmatic path forward. Prioritizing these areas would improve statistical confidence and sector-wide comparability while maintaining operational feasibility.

10.3. METHODOLOGICAL AND MODELING RECOMMENDATIONS

A key lesson learned—based on the comparative analysis as well as on the extensive stakeholder consultation throughout the study—is that methodological choices remain a major source of variability in reported carbon footprint results, even when identical primary datasets are used. Differences observed between the CFP and the 4C tool were primarily linked to emission-factor selection and modeling assumptions for specific sources, notably fertilizers and crop residue management. This underscores the need for transparent documentation of assumptions and cautious interpretation of absolute values, particularly when results are used for external reporting, target-setting, or supplier engagement.

The following sections examine key methodological design considerations that influence baseline results, including sampling representativeness, residue and wastewater modeling, fertilizer nitrogen specification, and LUC treatment. Together, they clarify how structural assumptions and study design choices shape carbon footprint outcomes and inform future alignment within the sector.

10.3.1. RESIDUE MANAGEMENT AS A STRUCTURAL DESIGN PARAMETER

Crop residue management emerged as one of the most relevant emission sources across countries, particularly where residues are left on the field and where anaerobic treatment pathways lead to methane formation. The study additionally confirmed that current survey approaches requiring farmers to report percentage shares of residues allocated to different management options (e.g., mulching, composting, piling, off-farm removal) introduce substantial uncertainty.

This uncertainty is structural rather than incidental. Residue streams are often heterogeneous, temporally variable, and managed through multiple practices applied sequentially or simultaneously. Farmers rarely track residue quantities in measurable units, making percentage-based reporting inherently subjective. While quality-control procedures and literature-based plausibility checks within this study helped constrain implausible values, these measures cannot fully compensate for ambiguity in the underlying mass flows.

Future studies should therefore move toward quantitative or semi-quantitative residue characterization, grounded in physically consistent mass-balance approaches. Examples include estimating residue quantities as functions of yield (e.g., pulp-to-cherry ratios), tree age, or pruning cycles, and linking treatment pathways to volumetric or mass-based proxies rather than percentages alone. Implementing such approaches requires explicit agreement at the study-design stage, impacting

sampling efforts, agronomic reference data choices, and primary calculation tool selection.

To immediately operationalize this recommendation for further research and industry alignment, the Sustainable Coffee Challenge plans to establish a technical taskforce—potentially in partnership with the Cool Farm Alliance (CFA)—to address this matter. CFA is already pursuing work to propose a more realistic data entry for pruning practices on coffee farms. This study can be leveraged to encourage stretching beyond the current boundaries of CFP to highlight such areas for improvement, and to explore more mass-balance/improved default values for residue management.

10.3.2. ALIGNMENT ON WASTEWATER MANAGEMENT

Wastewater generated during coffee processing has the potential to contribute significantly to methane emissions under anaerobic conditions and can therefore represent a material source of GHG emissions in on-farm coffee production systems, where wet processing and on-site treatment are prevalent. At the same time, the accurate quantification of wastewater-related emissions is highly sensitive to assumptions regarding wastewater volumes, organic load expressed through COD or BOD, and treatment pathways. These parameters vary substantially across processing methods, facilities, and regions, and there is currently no broadly agreed, sector-wide methodology for consistently characterizing coffee wastewater across origins. As a result, wastewater emissions represent one of the areas with the greatest methodological uncertainty and divergence across existing coffee carbon footprint studies.

Given this lack of alignment and the potential for wastewater assumptions to have a significant influence on final emission estimates, this study emphasizes the need for cautious treatment of wastewater emissions within current baseline assessments, and for clear delineation in system boundary definitions. Where data limitations prevent robust and comparable estimation, excluding wastewater emissions from aggregated footprint results, while transparently documenting both the exclusion and its rationale may even be preferable to including highly uncertain estimates that could obscure priority emission drivers or lead to inconsistent conclusions across studies.

In the present study, wastewater emissions were retained despite these uncertainties in order to preserve system completeness and comparability across tools, and to avoid systematically underestimating emissions in contexts where wet processing is prevalent. However, this decision further highlights the need for improved sector-wide methodological alignment, both for wastewater characterization and for the consistent incorporation of post-harvest processing stages beyond the farm gate. Developing harmonized approaches to integrating processing emissions is essential

to provide a more complete and comparable picture of supply chain emissions across origins and studies.

Overall, wastewater represents a highly relevant mitigation domain for the coffee sector, as effective wastewater management can deliver substantial and measurable emission reductions through improved treatment practices, reduced anaerobic conditions, or methane capture. Fulling understanding the mitigation potential and relevant approaches requires increased methodological alignment across the sector, including the development of harmonized and approved approaches for characterizing coffee wastewater. This includes clear guidance on COD and BOD measurement, sampling frequency, seasonal representativeness, and the consistent classification of treatment pathways. Targeted measurement campaigns at representative processing facilities would support the derivation of context-specific organic load ranges linked to different processing methods, and enable progression toward more robust estimation approaches over time.

Strengthening methodological alignment in this area would not only improve the comparability and credibility of coffee carbon footprint baselines, but also provide a more reliable foundation for identifying, prioritizing, and tracking wastewater-related mitigation strategies into the future. As such, wastewater management should be treated as both a methodological priority and a strategic opportunity for climate action within future coffee sector assessments. Indeed, the Sustainable Coffee Challenge also aims to leverage this study to explore mass-balance/improved default values for wastewater going forward, in addition to focusing on residue management.

10.3.3. FERTILIZER NITROGEN CONTENT AS A PRIMARY EMISSION DRIVER

Fertilizer production and application were consistently identified as the dominant contributors to farm-gate emissions across countries. Within this category, nitrogen content, not total fertilizer mass, is the primary driver of both upstream production emissions and direct and indirect soil N_2O emissions.

The study relied on farmer-reported fertilizer types and application rates, supplemented by default nitrogen contents where formulation details were incomplete. While consistent with common practice and CFP requirements, this approach highlights a critical limitation: uncertainty in nitrogen content propagates non-linearly into emission estimates. This is particularly relevant for compound fertilizers (e.g., NPK blends), where reported formulations may reflect commercial labels or blending locations rather than the origin and production pathway of the nitrogen component.

Improved differentiation of fertilizer nitrogen content, origin, and formulation would substantially enhance result robustness. However, achieving this requires clear ex-ante decisions regarding data granularity, acceptable default values, and the trade-off between localization and cross-country comparability. These decisions also directly affect survey length, enumerator training requirements, analytical complexity, and tool compatibility.

10.3.4. IMPLICATIONS FOR STUDY OBJECTIVES AND DESIGN

The findings demonstrate that post-data-collection methodological refinement is inherently limited. Once survey instruments, sampling strategies, and calculation tools are fixed, the scope of feasible analyses becomes constrained by the structure and resolution of the collected data. While post-hoc quality control, standardization, and sensitivity analysis can improve interpretability, they cannot substitute for missing or ambiguously defined parameters.

For future baseline studies, it is therefore strongly recommended that sample size, archetype analysis, residue management characterization, fertilizer nitrogen specification, and more be treated as priority design questions, explicitly resolved before finalizing study objectives and goals. Where these topics are expected to play a central role in mitigation analysis or target-setting, objectives should be framed accordingly, and sufficient resources allocated to:

- Ensuring a sampling size capable of capturing management heterogeneity;
- Defining and setting up an archetypal analysis, with the capacity to produce archetypal baselines;
- Driving methodological alignment between tools and emission-factor choices;
- Articulating specific tool capabilities and limitations;
- Providing sufficient enumerator training tailored to technically demanding parameters.

Embedding these considerations at the design stage will enable more robust downstream analysis and strengthen the actionability of results.

10.3.5. LAND USE CHANGE

While LUC was assessed using Tier-1 approaches and complementary tools (i.e., the 4C tool), the study confirms that farm-level self-reporting alone is insufficient to robustly capture historic land conversion, particularly where events occurred many years prior to the survey. Consistent with IPCC guidance, farms reporting LUC prior to 2005 were excluded from the analysis, as such conversions fall outside the 20-year attribution period. In addition, only direct LUC could be assessed with the available self-reported

data, cropland-to-cropland transitions were not considered LUC, and all eligible LUC emissions were amortized over 20 years and allocated across farm outputs in line with GHGP requirements. For the LUC assessment, farmers were asked to report the year and previous land use as well as their tillage system (full, reduced, or no-till) and general soil-input level, such as whether manure or other organic inputs were applied, as these determine the appropriate IPCC soil-carbon factors.

Despite applying these standardized methods, the LUC analysis remains constrained by the limitations of self-reported farm data, which often lack precise information on the timing and nature of land conversion and cannot be independently validated. Because no geospatial, cadastral, or jurisdiction-level land-use datasets were available to corroborate farmer-reported histories, the resulting estimates provide only indicative insights rather than fully GHGP-compliant LUC accounting. Due to these data limitations, the resulting LUC estimates were not integrated into the main CFP baseline. This underscores the need for stronger traceability systems with spatial information, more consistent producer recordkeeping, and future integration of remote-sensing or national LULUCF data to improve the reliability and auditability of LUC assessments. Strengthening these elements will allow subsequent reporting cycles to incorporate land-use change more accurately and with significantly reduced uncertainty.

10.3.6. CARBON SEQUESTRATION AND NON-CROP BIOMASS

The inclusion of non-crop woody biomass represents an important step toward more comprehensive carbon accounting in coffee systems. However, current tools and datasets remain insufficient to fully integrate sequestration into net carbon footprint results in a consistent and comparable manner. Soil carbon processes, including periodic soil measurements and tracking changes in soil organic carbon over time, are also essential for more accurately capturing long-term sequestration potential. Strengthening efforts related to soil carbon, biomass organic carbon (BOC), and regenerative agricultural practices will help improve the robustness of future assessments. Continued methodological development is required before such estimates can be used in decision-critical contexts.

In line with the LSRG GHGP, removals are reported distinctly from emissions and only where they are attributable to in-boundary activities, quantifiable with IPCC-consistent methods, and supported by clear evidence of additionality, ownership, and durability with a reversal-risk management approach. Given current data constraints, particularly limited re-measurement of soil carbon and non-crop biomass, incomplete geospatial verification, and high uncertainty sequestration estimates presented here are indicative and are not used to neutralize residual emissions. Future cycles will prioritize plot-level baselines, periodic re-measurement or calibrated

modeling, and uncertainty management to enable fuller alignment with the LSRG for removals reporting.

10.3.7. USE OF BASELINES FOR THE COFFEE SECTOR

The study demonstrates that national-level baselines can be credibly established through pre-competitive collaboration, harmonized data collection, and transparent uncertainty assessment. By applying consistent system boundaries, functional units and aligned methodological documentation across countries, the study provides a structured reference point for understanding emission magnitudes and dominant sources within major coffee-producing origins.

These baselines are well suited for benchmarking at the sectoral level, hotspot identification, scenario analysis, and strategic planning. They enable supply-chain actors to understand where emissions are concentrated, how results vary across production systems, and where mitigation resources may have the greatest systemic impact. However, national baselines should not be misconstrued as farm-specific performance benchmarks, compliance thresholds, or procurement decision tools. Farm-level emissions are inherently heterogeneous and reflect site-specific management, agroecological conditions, and historical factors that cannot be fully captured by national averages.

Consistent with perspectives emphasized by CIRAD, national baselines are most appropriately interpreted as structural reference frameworks rather than normative performance standards. They provide a macro-level understanding of system characteristics and emission drivers, but do not replace the need for farm-level diagnostics when designing targeted mitigation interventions. Moreover, baselines should be viewed as dynamic rather than static benchmarks; they may evolve as methodologies improve, data quality increases, and sector-wide alignment progresses.

When used appropriately, national baselines can support transparent communication, collective target-setting discussions, and coordinated climate action within the coffee sector. Their value lies not in ranking individual farms, but in informing collaborative mitigation pathways grounded in a shared and methodologically transparent understanding of emission patterns.

11. CONCLUSION AND USE CASES

11.1. INTRODUCTION

This study established national farm-gate-level carbon footprint baselines for coffee production across five major Latin American origins, using harmonized primary data collection and aligned carbon accounting methodologies. The baselines are intended to support sector-wide benchmarking, Scope 3 GHG accounting, and the identification and prioritization of on-farm mitigation opportunities; they are explicitly designed for aggregated analysis rather than precise quantification of emissions at the individual farm level. By applying a representative sampling framework and cross-validating results from the primary calculation tool using two independent methodologies, the study further provides a consistent, comparable basis for understanding broad emission drivers across diverse coffee production systems.

11.2. APPLICATION OF THE BASELINES IN CORPORATE ACCOUNTING AND SOURCING

As stated, the national-level baselines generated by this study are well suited for benchmarking, hotspot identification, and strategic planning, while not being misconstrued as farm-level performance benchmarks. They can support corporate Scope 3 Category 1 (Purchased Goods and Services) GHG inventories, particularly where primary farm-level data are not yet available. Companies may apply the baselines as conservative default emission factors for sourcing regions and progressively replace them with supplier-specific data as data maturity improves. In this way, the baselines provide a bridge between high-level accounting requirements and farm-level engagement.

Beyond inventory reporting, the baselines offer a reference point for contextualizing supplier-reported footprints; identifying emission hotspots; assessing opportunities for further research; and prioritizing countries, regions, or farm types/practices for targeted climate action. When used in conjunction with sourcing and sustainability programs, the results can inform the design of mitigation strategies focused on dominant emission drivers rather than diffuse or marginal sources. The baselines should therefore be understood as decision-support tools, not as fixed performance benchmarks for individual farms, nor as compliance thresholds or farm-level ranking instruments, but as strategic tools to guide investment, engagement, and continuous improvement across coffee supply chains.

11.3. ROBUSTNESS AND INTERPRETATION

By applying a representative sampling framework and cross-validating results from the primary calculation tool using two independent methodologies, this study provides a consistent, comparable basis for understanding broad emission drivers across diverse coffee production systems. While large-scale, multi-country agricultural assessments inevitably involve uncertainty, the results are considered robust and decision-relevant. This consideration is supported by the sampling design, the limited influence of statistical outliers across major emission sources, the consistent identification of dominant emission drivers across countries, and the close alignment between primary and comparative calculation approaches. Together, these elements indicate that the baselines provide conservative and credible estimates suitable for strategic analysis, benchmarking, and mitigation planning at national and sectoral scales, when interpreted within their defined methodological boundaries.

These methodological boundaries include reliance on farmer-reported activity data for some parameters, the use of default or literature-based emission factors where primary information was unavailable, and the exclusion of SOC dynamics and LUC from the system boundary. In addition, the baselines represent a single production year and therefore do not capture interannual variability, nor do they consider processing post farm-gate These limitations affect absolute emission values in kg of CO_2-eq per kg GBE up to export, but they do not undermine the internal consistency of the dataset, the identification of relative emission patterns and dominant sources, or the suitability of the results for comparative and decision-support purposes.

11.4. EMISSION REDUCTION PATHWAYS AND FUTURE METHODOLOGICAL REFINEMENT

Across all five countries, emissions from coffee production are concentrated in a limited number of on-farm processes, primarily fertilizer inputs, and crop residue and wastewater management. These sources dominate because of both their quantitative importance and the sensitivity of biologically-driven emissions to management practices. In contrast, emissions from fuel and energy use, pesticides, and transport are generally small in relative terms and therefore offer more limited mitigation potential at scale.

The concentration of emissions indicates that targeted interventions focused on nutrient management and organic matter handling are likely to deliver the largest reductions relative to effort. High-level mitigation opportunities include improving nitrogen-use efficiency through optimized fertilizer application rates, timing, and formulation; adopting improved crop-residue and wastewater management practices that reduce anaerobic decomposition and methane formation; and strengthening

agronomic advisory services to support efficient, site-appropriate input use. Productivity improvements that reduce emission intensity per unit of output without increasing absolute emissions represent an important complementary pathway, particularly in systems where yield responses remain below observed efficiency thresholds.

Looking forward, future assessments could be strengthened through increased use of farm-level records to reduce recall uncertainty; multi-year data collection to capture temporal variability; improved differentiation of fertilizer nitrogen content and origin; enhanced approaches to estimating emissions from residue and wastewater management; and the inclusion of soil and agroforestry carbon stock dynamics once methodologies are sufficiently mature and consistently applicable to perennial systems. At the same time, this study demonstrates that large-scale, pre-competitive primary data collection using harmonized tools is both feasible and effective for generating representative sectoral baselines. This establishes a foundation for iterative refinement of both methods and mitigation strategies through continued collaboration, provided that key analytical parameters are explicitly aligned at the study-design stage.

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13. ANNEXES

- Annex 1: LAND USE CHANGE
- Annex 2: INTERCROP TREE SPECIES LIST
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13.1. ANNEX 1: LAND USE CHANGE

The Greenhouse Gas Protocol (GHGP) Land Sector and Removals Standard (LSRS) provides three approaches for land use change (LUC) accounting: Land Management Unit (LMU)-level direct LUC (dLUC); jurisdictional direct LUC (jdLUC); and statistical LUC (sLUC). Companies select among these methods based on the level of traceability and the granularity of land-use information available within their value chain (Figure 38). LMU-level dLUC estimates emissions from land conversion on specific, traceable plots, and requires farm-level spatial data. Jurisdictional dLUC serves as an intermediate option, using spatially explicit data for a defined sourcing area when plot-level data are not available. In contrast, sLUC estimates emissions across an entire jurisdiction, such as a country, region, or municipality, and allocates those emissions across all products produced in that jurisdiction without requiring spatially explicit, farm-level information.

Scope 3 spatial boundary	Statistical land use change (sLUC)	Direct land use change (dLUC)	
		"Jurisdictional" direct land use change (jdLUC)	"LMU-level" direct land use change
Global	■		
Jurisdiction	■	■	
Sourcing region	■	■	
Land management unit (LMU)			■
Harvested area			■

■ Calculation approach is applicable   ■ Calculation approach not applicable

Figure 38.Land use change emissions calculation approaches based on value chain traceability (source: GHGP LSRG figure 7.1)

For country-level emission factors, only jdLUC and sLUC are applicable because LMU-level dLUC requires traceability to individual land parcels and therefore cannot be derived from national-scale average datasets. While a statistical LUC approach would ordinarily be appropriate when using jurisdiction-level emission factors, the LUC information collected through the 4C tool is derived exclusively from farm-level, self-reported data. As such, the dataset inherently supports only a direct LUC (dLUC) assessment.

Because sLUC requires jurisdiction-level data sources, such as national land-use, land-use change and forestry and (LULUCF) inventories, land-cover change statistics, or remote-sensing time-series datasets, the farm-level 4C dataset cannot be scaled up to

represent jurisdiction-level land-use dynamics. In other words, the sampled, self-reported farm data do not constitute a complete or representative jurisdiction-wide dataset and therefore cannot be used to create an sLUC proxy. The 4C analysis is necessarily a direct LUC analysis, and any attempt to generate jurisdiction-level or statistical LUC values from this dataset would fall outside the methodological requirements of the GHGP LSRS.

Under GHGP guidance, any dLUC-related emissions must be allocated across all products produced on the affected farm using an appropriate allocation method. The 4C tool follows this requirement by distributing LUC-related emissions proportionally across all relevant outputs from each farm in the reporting year. Also consistent with IPCC guidance and GHGP LSRS requirements, LUC emissions were amortized using a linear 20-year allocation approach. Total carbon stock changes from reported land conversion were additionally divided evenly across a 20-year period, following the IPCC 20-year amortization method.

Despite limitations, LUC estimation was conducted using the 4C tool, applying IPCC Tier 1 default values where necessary and using farmer-reported data to estimate emissions associated with land conversion within the 20-year attribution window. Farms reporting LUC prior to 2005 were excluded because such events fall outside the attribution period. Likewise, farms indicating cropland as their previous land-use category were not considered LUC cases, as such transitions do not meet IPCC criteria for land-use change (IPCC. 2019, Chapter 3.3: Cropland). Changes in management practices on these farms were analyzed separately later on this section under the title "*Farms that reported cropland as previous land use section*".

Data collection for LUC at the farm level presented notable challenges. Many farmers lacked historical land-cover records or were unable to recall the exact year or type of LUC, especially where conversion occurred many years before data collection. As a result, this analysis reflects the best available survey evidence, but it underscores the need for more robust traceability mechanisms and more systematic LUC-related data collection across coffee supply chains.

Although the LUC analysis is constrained by methodological limitations and the uncertainty inherent in farmer self-reporting, the results still provide valuable indicative insights into the range and approximate timing of land-use transitions occurring within the sampled production landscapes. These high-level patterns are useful for preliminary risk identification, flagging areas where deeper geospatial validation may be required, and informing improvements to traceability systems within certified supply chains. However, due to the absence of independent corroboration—such as satellite-based land-cover histories, cadastral documentation, or, as noted, jurisdictional land-use datasets—these results do not meet the methodological robustness required for full GHGP-compliant LUC accounting. For this

reason, and to avoid overstating uncertain contributions, the LUC-related carbon stock change estimates were not integrated into the core national farm-level baselines and are presented separately for transparency.

Looking ahead, future research would benefit from integrating farmer-reported information with independent geospatial data sources such as remote sensing-based land-cover change maps, national LULUCF inventories, and longitudinal spatial analyses capable of verifying the timing and extent of land-use transitions. Such triangulation would significantly improve the accuracy, reproducibility, and auditability of LUC assessments and would allow more robust incorporation of LUC impacts into CFP accounting frameworks uncertainty.

LUC results per country

Summary

Table 40 below summarizes the extent and impact of LUC across countries in the study, using the described methodology. Brazil Robusta showed the highest proportion of farms with LUC (44.5%), primarily transitioning from grassland, resulting in 6.608,09 t CO_2eq emissions. Mexico, despite having only 2.7% of farms with LUC, exhibited the highest intensity in kg CO_2-eq per kg GBE (0.10 kg CO_2-e per kg GBE), driven by shrubland conversions. Peru and Colombia reported moderate LUC shares (6.3% and 11.6%, respectively), but their emission intensities per kg GBE were significantly higher than Brazil Arabica and Robusta due to smaller production volumes. Honduras had the lowest LUC-related emissions and intensity among the assessed countries.

COUNTRY	Farms with LUC (%)	Dominant transition	LUC total (t CO_2-eq)	LUC (kg CO_2-eq per kg GBE)	GHG from cultivation kg CO_2-eq per kg GBE	LUC +Final intensity 4C kg CO_2-eq per kg GBE
BRAZIL ARABICA	22.8%	Grassland (81)	4.789	0.02	2.67	2.69
BRAZIL ROBUSTA	44.8%	Grassland (132)	6.608	0.06	1.91	1.97
COLOMBIA	11.6%	Grassland (32)	169	0.08	5.43	5.51
HONDURAS	3.2%	Grassland (11)	37	0.01	4.07	4.08
MEXICO	2.7%	Shrubland (6)	393	0.10	1.25	1.35
PERU	6.3%	Grassland (7)	125	0.07	1.81	1.88

Table 40: GHG emissions + LUC Results per Country

RESULTS FOR BRAZIL ARABICA

Across 501 Arabica farms, 114 reported LUC (22.8%) in Brazil. The transition profile is dominated by transition from grassland (81 farms), followed by cropland (23 farms, which were not accounted for in the results), forest land (9) and shrubland (1). Timing of LUC shows a strong recent signal with 38 cases between 2006 and 2015, and 56 between 2016 and 2025. In total, 20 farms transitioning before 2005 were excluded. Brazil's higher prevalence of LUC reflects dynamics of cropland expansion from pasture/grassland. Although transition from grassland to cropland is less carbon-intensive than the transition from forest to cropland, the scale and recency of expansion warrant increased focus.

RESULTS FOR BRAZIL ROBUSTA

In Brazil's Robusta system, 172 out of 387 farms (44.5%) reported LUC, the highest proportion among all origins. Transitions were overwhelmingly from grassland (132 farms), followed by cropland (33 farms, excluded from results per IPCC guidance) and a smaller number from forest land (7 farms). Timing data show a strong concentration of recent conversion, with 58 cases between 2006 and 2015 and 107 between 2016 and 2025, while 7 farms reporting transition before 2005 were excluded. The combination of a very high LUC incidence and extensive recent grassland conversion drives one of the largest total LUC emissions in the dataset, indicating ongoing expansion dynamics in Robusta-producing landscapes.

RESULTS FOR COLOMBIA

In Colombia, 69 out of 597 farms (11.6%) reported LUC. In total, 32 farms transitioned from grassland, 25 from other cropland, and 12 from shrubland. No farms reported conversion from forest land. In terms of timing weights, 18 farms were transitioned between 2006 and 2015, and 46 were transitioned between 2016 and 2025. Three were transitioned before 2005, which were excluded from the analysis, as were the 25 farms that transitioned from other cropland, as per IPCC guidance.

RESULTS FOR HONDURAS

In Honduras, 19 out of 589 farms (3.23%) reported LUC, led by transitions from grassland (11 farms), cropland (3 farms, which were not accounted for in the results), shrubland (3 farms), and forest land (1 farm). Timing of LUC includes 7 farms converting between 2006 and 2015, and 5 farms between 2016 and 2025. In total, 5 farms reporting transition before 2005 were excluded from the analysis. Overall, LUC is low to moderate in Honduras. The limited forest conversion suggests lower carbon intensity compared to countries with higher

deforestation signals, but grassland conversions still contribute to emissions. The balanced timing indicates that changes are not concentrated in recent years, reducing the likelihood of sharp short-term impacts; however, there remains a persistent underlying risk.

RESULTS FOR MEXICO

In Mexico, 16 out of 604 farms (2.7%) reported LUC, dominated from 6 farms converting from forest land, 6 from shrubland, 2 from cropland (not accounted for in the results), and 2 from grassland. All changes were between 2016 and 2025. The combination of forest conversion and recent timing produce large product-level additions, making Mexico the highest-level impact origin for LUC emissions per kg GBE. This is consistent with regional patterns in recent primary forest loss and fire-driven clearing[39].

RESULTS FOR PERU

In Peru, 39 out of 619 farms (6.30%) reported LUC, led by transitions from cropland (25 farms, which were not accounted for in the results), grassland (7 farms), shrubland (4 farms), and forest land (3 farms). The timing of these instances is concentrated between 2006 and 2015 (13 farms), and 2016 and 2025 (26 farms). No transition before 2005 was reported. Although overall LUC incidence in Peru is moderate, the combination of recent timing and the presence of forest related transitions indicates a continuing land use pressure that contributes to nonnegligible emissions and signals ongoing landscape change.

Farms that reported cropland as previous land use

A total of 77 farmers reported that their previous land use was cropland, which means there was no change in the land use category. While these cases were not included in the LUC calculation and results, these farmers did report changes in their management practices, providing important information about sustainability trends.

Overall, most farmers reported LUC that involved shifts in soil and residue management practices. In the context of the LUC methodology, tillage information is used to determine the appropriate IPCC soil carbon stock change factor, since full tillage, reduced tillage, and no-till systems correspond to different default soil carbon dynamics. Regarding previous tillage practices, most farmers used reduced tillage; a smaller share used full tillage; and a minority reported no-till. Because reduced- and no-till systems disturb the soil less than full tillage, they are associated with slower

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[39] Goldman, E., Carter, S., & Sims, M. (2025). Fires drove record-breaking tropical primary forest loss in 2024. World Resources Institute; Global Forest Watch. https://www.globalforestwatch.org/blog/data-and-research/fires-drove-record-breaking-tropical-primary-forest-loss-in-2024/

decomposition of soil organic matter and higher soil carbon retention under IPCC Tier-1 guidance.

Looking at changes in soil and residue inputs relative to previous practices, nearly half of the farmers reported increasing residue return to the field (classified as medium level). About one-third reported maintaining low residue return, without adding manure or mineral fertilization, indicating little change in inputs. A smaller proportion reported adding animal manure or substantially increasing residue inputs compared to previous management. Under IPCC guidance, higher residue retention and organic input additions influence how organic matter decomposes, but their net effect on emissions depends on subsequent management and was not quantified in this study.

Even though the land use stayed the same, many farmers improved their soil management by keeping more crop residues on the field and, in some cases, by adding organic matter through manure.

Overall considerations

LUC had a relatively low frequency within the sample, but a considerable influence on product-level emissions, especially in Mexico, Peru, and Colombia, due to recent forest and shrubland conversions. In Brazil Arabica, although more farms reported land-use change, most transitions were from grassland to coffee cultivation. Because grassland has a lower carbon stock, many of these transitions occurred earlier, and coffee production volumes are higher, the resulting emissions per kilogram of coffee are comparatively lower. In Brazil Robusta, a larger share of farms reported LUC (44.5%), also predominantly grassland-to-coffee conversions. While total LUC emissions were higher than Arabica, the per-kg impact remained moderate (0.06 kg CO_2-eq/kg GBE) due to high production volumes. Finally, LUC in Honduras had a lower impact on overall emissions.

Despite data gaps, no geospatial verification, Tier-1 factor/20-year amortization assumptions, allocation sensitivity, pre-2005 exclusion effects, land-use misclassification risk, and sample representativeness constraints, this analysis remains relevant as it highlights where stronger traceability and improved monitoring are most needed. Future work should integrate independent spatial data sources, strengthen historical land-use documentation, and expand sample coverage to reduce uncertainty and enable more robust, GHGP-aligned reporting. This is critical for ensuring that LUC-related risks are identified early and transparently reflected in sustainability reporting.

13.2. ANNEX 2: INTERCROP TREE SPECIES LIST

No.	Tree species name
1	Acacia Acacia oraria/Acacia mangium
2	African teak Moraceae
3	African tulip tree Spathodea campanulata
4	Avocado Persea americana
5	Cashew Anacardium occidentale
6	Cassia Cassia fistula
7	Coconut palm Arecaceae
8	Conifer forests Default
9	Custard Apple Casimiroa tetrameria
10	Croton tree/Mukinduri Croton megalocarpus
11	Durian Durio zibethinus
12	Banana Musa spp.
13	Egyptian riverhemp Fabaceae
14	Ficus ovata Ficus padifolia
15	Fig-mulberry Ficus padifolia
16	Flame tree Erythrina abyssinica
17	Fruit Tree Default
18	Giant Lira Melia azedarach
19	greenheart tree Ocotea psychotrioides
20	Guava Psidium guajava
21	Hopea Hopea odorata
22	Inga species various
23	Jacaranda Jacaranda mimosifolia
24	Jackfruit Artocarpus
25	Kapok Ceiba pentandra
26	Lemon Citrus limon
27	Listea Litsea Lauraceae
28	Loquats Rosaceae

No.	Tree species name
29	Macadamia Proteaceae
30	Mango Mangifera indica L
31	midnight horror Oroxylum indicum
32	Moringa/Drumstick tree Moringa oleifera
33	Nile tulip Markhamia lutea
34	Oranges Citrus sinensis
35	Papaya Carica papaya
36	Parasol tree Malvaceae Firmiana colorata
37	Pepper Piperaceae Piper arthante
38	Pinus species Pinaceae Pinus sylvestris
39	Plantain Musa paradisiaca
40	Plantation teak/Common teak Tectona grandis
41	Quercus Species various
42	Quickstick Gliricidia sepium
43	Red Stinkwood Prunus Rosaceae Prunus arborea
44	Royal Poinciana/flame tree Delonix regia
45	Rubber Hevea brasiliensis
46	Southern Silky Oak Proteaceae
47	Spiked Powder Puff Leguminosa (Fabaceae)
48	Strangler Fig Moraceae Ficus
49	Sudan teak Boraginaceae Cordia (Various)
50	Tamarind Fabaceae
51	Umbrella tree Araliaceae Schefflera
52	Wild tamarind/red leucaena Fabaceae Leucaena leucocephala
53	Tropical trees (Dry)
54	Tropical trees (Moist)

13.3. ANNEX 3: COMPOSITION OF TECHNICAL SERVICE PROVIDER

Meo Carbon Solutions was the key Technical Service Provider for this study, together with the participation of Global Risk Assessment Services (GRAS) and 4C Services. Together, this team led the technical assessment for the **Latin America Coffee Carbon Footprint Baseline Study,** producing robust analysis for Brazil, Colombia, Honduras, Mexico, and Peru.

Meo Carbon Solutions (MCS): Meo Carbon Solutions is an independent consulting company with long-standing experience in sustainability, providing services globally for public and private-sector clients. MCS's projects regularly involve stakeholders from industry, agriculture, NGOs, research institutions, and public authorities. MCS's GHG analysis for production chains covers activities such as cultivation, processing, storage, transportation, and distribution to the final client. In the past, MCS has completed a variety of different projects for the coffee sector; for example, they have worked with the USAID GIA (2023) project to calculate a national baseline for Indonesia and Vietnam; and with the University of Tokyo to calculate GHG emissions in Brazil, Colombia, and Vietnam. In addition, within the scope of the develoPPP project, MCS performed a baseline GHG emission calculation for the coffee supply chain in Tanzania, followed by supporting the implementation of emission-reduction activities and monitoring future emissions. MCS also implemented an improvement strategy for a European roasting facility to produce low-emission roasted coffee beans, and guided other carbon-neutrality strategies. Several projects in coffee sourcing origins have estimated GHG emissions and supported implementation improvements to help supply chains achieve the 4C climate-friendly coffee certification.

Global Risk Assessment Services (GRAS): GRAS is an innovative, reliable, and transparent service provider that leverages advanced remote sensing and geospatial technologies, as well as social risk assessments, to support businesses, organizations, and governments with objective data, customized solutions, and platforms to make informed decisions and drive positive change in their supply chains. With over a decade of global experience across multiple

countries and crop types, GRAS has successfully supported a diverse range of clients committed to sustainability and no deforestation. GRAS specializes in implementing zero-deforestation strategies, mapping and managing sustainability risks in agricultural production areas, establishing secure and efficient monitoring systems for global supply chains, and supporting credible and cost-efficient certification processes. GRAS uses state-of-the-art technologies and methods enabling transparent, fast, and reliable results, offering advanced solutions and platforms. GRAS has delivered several projects on coffee, including sustainability risk assessments for coffee farmers in Mexico, improving traceability within coffee supply chains using innovative technologies, risk assessment and LUC analyses for a German government co-funded project in Tanzania, and national baselines calculations for Indonesia and Vietnam under USAID GIA.

4C Services: 4C is an independent, stakeholder-driven, internationally recognized third party certification system for coffee and cocoa. 4C has recently changed its name to *Certification for Climate, Conservation, and Communities* to reflect its new holistic approach to sustainability certification. Active in 19 producing origins, it connects farmers to sustainable markets and enables its system users to participate in responsible supply chains that support economic resilience, fair and safe working conditions, and the conservation of ecosystems and biodiversity. With improvements over time, the 4C System has proven to be a robust, independently benchmarked standard, and defines clear criteria for sustainable practices across three interconnected dimensions—social, environmental, and economic. It also offers innovative, reliable industry solutions to comply with global regulations in a changing landscape, including its 4C Add-Ons to the existing core certification. These include the Carbon Footprint, Food Security, and Empowering Equity: Empowering Women Add-ons. Specifically, the 4C Carbon Footprint Add-on enables companies and users to calculate the carbon footprint of their coffee and cocoa supply chains, supporting emissions reduction in supply chains.

13.4. ANNEX 4: SECONDARY DATA SOURCES

SECONDARY DATA SOURCES AT NATIONAL AND REGIONAL LEVEL

COUNTRY	INSTITUTION	YEAR OF DATA	SOURCE LINK
BRAZIL	CONAB - Companhia Nacional de Abastecimiento (EN: National Company of Supply)	2022	https://portaldeinformacoes.conab.gov.br/produtos-360.html
	Instituto Brasileiro de Geografia e Estatística (EN: Brazilian Institute of Geography and Statistics)	2022	https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9117-producao-agricola-municipal-culturas-temporarias-e-permanentes.html?=&t=resultados
	ABIC - Associação Brasileira da Indústria de Café (EN: Brazilian Coffee Industry Association)	2023	https://www.abic.com.br/estatisticas/producao-agricola-2/
COLOMBIA	Federacion del cafe Colombiano (EN: Colombian Coffee Federation)	2022	https://federaciondecafeteros.org/app/uploads/2023/08/Precios-area-y-produccion-de-cafe2.xlsx
	Agronet - Ministerio de agricultura y desarrollo rural (EN: Ministry of Agriculture and Rural Development)	2022	https://www.agronet.gov.co/estadistica/Paginas/home.aspx?cod=1
	UPRA - Unidad de Planificación Rural Agropecuaria, Ministerio de Agricultura (EN: Rural Agricultural Planning Unit, Ministry of Agriculture)	2022	https://www.agronet.gov.co/estadistica/Paginas/home.aspx?cod=2
HONDURAS	IHCAFE - Instituto hondureno del cafe (EN: Honduran Coffee Institute)	2022	https://www.ihcafe.hn/produccion-nacional/
MEXICO	Servicio de Información Agroalimentaria y Pesquera - Gobierno de Mexico (EN: Agri-Food and Fisheries Information Service - Government of Mexico)	2022	https://nube.siap.gob.mx/cierreagricola/
PERU	Cámara Peruana del Café y Cacao (EN: Peruvian Chamber of Coffee and Cocoa)	2021	https://camcafeperu.com.pe/ES/cafe-peruano-estadisticas.php
	INEI - Instituto Nacional de Estadística e Informática (EN: National Institute of Statistics and Informatics)	2022	https://www.gob.pe/inei/ https://www.inei.gob.pe/media/MenuRecursivo/indices_tematicos/cap13002_3.xls
	Ministerio de desarrollo agrario y riego (EN: Ministry of Agrarian Development and Irrigation)	2022	https://app.powerbi.com/view?r=eyJrIjoiYjYwYTk5MDgtM2M0MS00NDMyLTgzNDEtMjNhNjEzYWQyOTNIIiwidCI6IjdmMDg0NjI3LTdmNDAtNDg3OS04OTE3LTk0Yjg2ZmQzNWYzZiJ9

Figure 39: Secondary Data Sources

13.5. ANNEX 5. REFERENCES - HETEROGENEITY ANALYSIS

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13.6. ANNEX 6. RANDOMIZATION PROTOCOL

RANDOMIZATION PROTOCOL

This document provides comprehensive guidelines for Supplier Partners and enumerators to ensure the proper implementation of randomization principles during the data collection process.

Protocol Guidelines:

When visiting farms in the designated municipalities, adhere strictly to the following randomization protocols to maintain data integrity:

- *Diversify Farm Visits:* Prioritize visits to sparsely located farms to enhance the variety of the sample pool, which can help mitigate sampling bias.
- *Avoid Bias in Farm References:* While surveyed farms can serve as a useful reference for identifying other potential sampling locations, avoid using references where they share similar characteristics (e.g., familial relations). This practice reduces the risk of introducing bias into the sampling process.
- *Re-allocation of Samples:* If the required number of samples from a target municipality cannot be obtained, enumerators are allowed to re-allocate the missing samples to adjacent municipalities within their assigned areas. Such re-allocations must be documented and reported promptly.

Best Practice Guidelines (applicable when practical):

Ensure Representation of Diverse Farm Types: To prevent sampling bias, avoid focusing exclusively on certified farms when there are both certified and non-certified farms in the supply chains. Include a random mix of certified and non-certified farms in your sample to ensure that the sample accurately reflects the entire population within the supply chain.

Importance of Adherence:

Strict adherence to these protocols is crucial to preserving the integrity and validity of the data collection process, ensuring that the findings are representative and reliable.

13.7. ANNEX 7. PESTICIDES LIST

PLANT PROTECTION (% OF ACTIVE INGREDIENT)

Name of active substance	Percentage of active ingredient	Name of active substance	Percentage of active ingredient
Abamectina	18	Dinotefuram; Flutriafol	36
Acetamiprid	20	DMA dicamba salt; 2,4-D amine salt	30
Acetamiprido; Bifentrina	50	Epoxiconazole	25
Azoxistrobina	50	Fipronil	20
Azoxistrobina; Cyproconazol	28	Flupiradifurona	20
Azoxistrobina; Difenoconazol	33	Glyphosate	48
Azoxystrobin	33	Imidacloprid	70
Boscalida	50	Imidacloprid; Bezacyfluthrin	30
Caldo	39	Imidacloprido;Triadimenol	42
Carbendazim	50	Indaziflam	50
Carbosulfan	30	Lufenrom	40
Cercobin (Tiofanato-metílico)	30	Maconzeb; Azoxistrobina;Tebuconazole	75
Chlorabtraniliprole; Thiamethoxam	30	Malathion	50
Chlorothalonil	72	Mancozeb	45
Chlorpyrifos	48	Manzozeb	48
Ciantraniliprole	10	Piraclostrrobina; Epixiconazol	18
Cletodim	24	Profenofos	72
Clorantraniliprole	35	Quinalphose	25
Clorpirifos	35	Tebuconazole	35
Cobre	69	Thiametoxam	25
Cooper oxychloride	50	Thiametoxam; Ciproconazol	50
Cypermethrin; Profenofos	45	Thiametoxam; Clorantraniliprole	30
Cyprocanazol	10	Trifloxistrobina; Ciproconazol	54
Cyproconazol; Tiametoxam	60	Trifloxistrobina; Tebuconazol	30
Dimethoate	29	Zapp	62

Source: https://www.epa.gov/ingredients-used-pesticide-products/brief-overviews-about-individual-pesticides