Review on Green Coffee Carbon Footprint

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Cirad report

Key outputs and recommendations

State-of-the-art of green coffee carbon footprint:

- *Across 34 studies, the median carbon footprint was 3.6 kgCO_{2eq}/kg green coffee (min: 0.15 kgCO_{2eq}/kg green coffee; max: 14.5 kgCO_{2eq}/kg green coffee). The great variability is due to both system diversity and methodological inconsistencies.*
- *Main contributors: Land Use Change (LUC), N-fertilisers, crop residues and wet process emissions; although, the two last items were not systematically accounted for.*
- *Main methodological inconsistencies: the modelling of the perennial crop, the biomass accounting, including Land Use and Land Use Change (LULUC), and the handling of co-products.*

Analysis of existing Carbon Footprint guidelines:

- *Main useful standards are the CFP-PCR (2013) for green coffee and the ISO 14067 for Carbon Footprinting. The CFP-PCR is the most specific and relevant to green coffee, but not comprehensive enough.*
- *We compiled (in section 2) all relevant guidance specific to green coffee (covering all Life Cycle Assessment (LCA) stages and providing details on Functional Unit, sampling and data quality, emission factors, interpretation, reporting and communication…).*
- *When a lack of clarity was identified, we provided extra guidance as detailed below.*

Recommendations on sampling and data quality:

- *We provide a decision tree to choose the best sampling approach depending on study goal, scope and constraints.*
- *Before using any statistical formula (which varies slightly depending on the guideline) we recommend designing the sampling protocol on a specific typology of the farms (and the post-harvest stages).*
- *Amongst the criteria to consider in the typology, we highly recommend: agroecological potential zones, cropping system category, fertiliser type and amount (especially N fertiliser), 1st processing technology.*
- *We recommend using the data quality rating system of PEFCR (2018) for an assessment of primary and secondary data against their precision, temporal, geographical and technological representativeness.*

Recommendations on the perennial cycle modelling:

- *We recommend the modelling of the whole perennial cycle based on a modular approach. Each module consists in a perennial development phase that should be characterised by an average dataset and multiplied by the phase duration. Inputs/outputs over the whole cycle are calculated as a weighted average.*
- *The number of phases and their respective durations may be site-specific but with a minimum of 3 phases. Uncertainty related to the phase durations and data quality may be tested through scenario analysis.*
- *For each phase, data should be collected for 2-3 consecutive years in order to smooth out climate variability.*
- *Nursery may be considered negligible from a carbon footprint point of view except for 3 specified cases: greenhouse nurseries; coffee density >5000 trees/ha; and coffee plantation <10 years lifespan.*

Recommendations on LULUC accounting:

- *We recommend applying IPCC 2006 Tier 1, Stock difference approach for both LUC and LU emissions, with a consistent 20-year timeframe applied for. LUC should be considered when occurring within the past 20 years; likewise, increased stocks within coffee plantations (i.e. LU) should only be considered if the management changes leading to increased stocks have been consistently applied for at least 20 years. Carbon stocks should be based on previous recommendations regarding biomass quantification and should be time-averaged in order to smooth out the long-term variations in planting cycles. Carbon stocks with a short lifespan (<2 years) should not be considered, i.e. dead organic matter and associated annual crops do not contribute to long-term carbon storage. On the contrary, these short-*

time pools contribute to residue emissions in the field, i.e. GHG emissions other than biogenic CO_2*, that should be accounted for.*
- *LULUC emissions should be calculated based on involved clearing processes, e.g. burning or decaying. Within LULUC, all greenhouse gases (GHG) are to be considered including biogenic* CO_2*.*
- *LULUC emissions should be linearly amortised over the perennial crop cycle, or over two cycles in the case of short-lived plantations, and over 20 years. Both results should be given.*
- *In the case of associated perennial crops, if allocation rules were applied throughout the assessment including in LULUC, both results with and without allocations should be displayed.*

Recommendations on biomass estimation:

- *We provide a range of allometric models to estimate the above and below-ground biomass of coffee trees and associated trees. These must be combined with tree densities and averaged over the whole duration of the coffee plantation.*
- *The biomass of associated trees is by far the largest pool of perennial biomass in agroforestry systems, higher than that of coffee trees, especially in complex agroforestry systems.*
- *Below-ground biomass of coffee can account for between 20 and 100 % of the above-ground biomass, but the range for coarse root is about 40 %. Additional studies with robust methodologies in a variety of coffee systems should refine the assessment of below-ground biomass in coffee plantations*

Recommendations on biochar:

- *There is strong scientific consensus that the mean residence time of biochar carbon in soil is higher than that of all other organic carbon compounds. Therefore, the large recalcitrant fraction can contribute directly to long-term C sequestration in soil. However, on the basis of current knowledge, it is not possible to say precisely for how long and with what long-term consequences for agro-ecosystems. However, no negative agronomic or environmental effects have been consistently demonstrated, so far, for any of the parameters evaluated regarding performance (e.g. yield) and environment.*
- *Residues from pruning of coffee bushes could be a more valuable source of biomass to produce biochar given the too low availability of coffee husk. There is a need to characterise the biochar from these residues, though, as there is yet no specific study assessing the agronomic impacts of such a biochar.*
- *Develop field experiments with biochar application, notably in coffee plantations, as most of the studies were carried out in laboratory conditions.*
- *Assess the LCA impacts of biochar production and application for coffee production.*

Recommendations on co-product management

- *Clearly identify all organic inputs and outputs susceptible of being considered as carbon sinks or sources (e.g. manure, crop residues, green coffee processing co-products).*
- *Build a mass balance of the production system, clearly identifying all raw materials and co-products together with their moisture contents.*
- *Build a baseline scenario representing the current situation of the system and including all potential sources of GHG emissions, to be compared with alternative scenarios where at least one management element is different.*

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Acronyms

ABG	Above Ground Biomass
BGB	Below Ground Biomass
CFP	Carbon Footprint of a Product
CFP-PCR	Carbon Footprint of a Product – Product Category Rules
DBH	Diameter at Breast Height
DM	Dry Matter
DOC	Degradable Organic Carbon
GAEZ	Global Agro Ecological Zones
GBE	Green coffee Bean Equivalent
GWP	Global Warming Potential
GHG	Greenhouse gas
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LULUC	Land Use Land Use Change
PCA	Principal Component Analysis
PCR	Product Category Rules
SOC	Soil Organic Carbon
wt%	Percentage by weight

Glossary

Below-ground biomass	All living biomass of live roots. Fine roots of less than (suggested) 2mm diameter are sometimes excluded because these often cannot be distinguished empirically from soil organic matter or litter.	Source : IPCC[1]
Biogenic carbon	Carbon derived from biomass (*i.e.* originating from atmospheric CO_2 and converted through photosynthesis) within a geological short time-frame (*i.e.* not fossilised). Biogenic carbon can be stored in the biosphere (*e.g.* vegetation or soil organic carbon) or released as gases (*i.e.* CO_x or CH_4).	Adapted source: ISO/TS 14067:2013
Biomass	Material of biological origin excluding material embedded in geological formations and material transformed to fossilised material, and excluding peat. Biomass includes organic material (both living and dead), *e.g.* trees, crops, grasses, tree litter, algae, animals, and waste of biological origin, *e.g.* manure.	Source: ISO/TS 14067:2013
Carbon footprint of a product - CFP	Sum of greenhouse gas (GHG) emissions and removals in a product system, expressed as CO_2 equivalents and based on a life cycle assessment using the single impact category of climate change. The CO_2 equivalent of a specific amount of a greenhouse gas is calculated as the mass of a given greenhouse gas multiplied by its global warming potential relative to that of CO_2. In LCA, this GHG balance is a midpoint impact whose indicator is usually named "Global warming impact". We use both CFP and global warming impact throughout the report. If both may refer to the same calculation, global warming impact is more appropriate for LCA studies.	Adapted source: ISO/TS 14067:2013
Carbon storage <in product>	Carbon removed from the atmosphere and stored as carbon in a product. According to the IPCC international consensus, carbon storage may be accounted for, within GHG assessment, only when lasting at least 20 years.	Adapted source: ISO/TS 14067:2013
Co-product	Any of two or more products coming from the same unit process or product system. In a broad sense, co-products can encompass valuable co-products as well as wastes. Wastes usually require further down treatment with both economic and environmental costs, but they may also be recycled.	Adapted source: ISO 14040:2006
Direct land use change - dLUC	Change in human use or management of land within the product system being assessed. According to IPCC, land use change	Adapted source: ISO/TS 14067:2013
Dry matter - DM	Equivalent to dry weight (dw) = wet weight * (1 - %moisture)	
Elementary flow	Material or energy entering the system being studied that has been drawn from the environment without previous human transformation,	Source: ISO 14040:2006

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[1] https://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/Glossary_Acronyms_BasicInfo/Glossary.pdf

	or material or energy leaving the system being studied that is released into the environment without subsequent human transformation.	
Foreground process	In LCA, foreground processes consist of processes most directly related to the activity or product under study, usually taking place where the end product is delivered. In agricultural LCA, foreground processes commonly consist of the farming activities and eventual post-harvest processing. By opposition, background processes are indirectly connected to the product of interest such as electricity production or transportation means and fuels.	Own
Fresh matter - FM	Equivalent to wet weight (ww) = dry weight / (1 - %moisture)	
Functional unit	Quantified performance relative to a given service or function provided by a product system and which is used as a reference unit	Adapted source: ISO 14040:2006
Global warming potential - GWP	Characterization factor describing the radiative forcing impact of one mass-based unit of a given greenhouse gas relative to that of carbon dioxide over a given period of time. The global warming potential of a given GHG depends on its radiative forcing over its lifetime in the atmosphere. It may hence vary depending on the integration time frame and other atmospheric parameters, such as feedbacks, used to model all GHG dynamics. Global warming potentials of C-based GHG vary depending on their fossil or biogenic origin. In the case of fossil ones, their GWP are the ones calculated in the atmosphere. In the case of biogenic C-based GHG, the C originates from atmospheric CO_2 and returns to the atmosphere quickly enough so as not to modify the greenhouse effect. Hence, to calculate the GWP of biogenic CH_4, for instance, the GWP of CO_2 embodied in the CO_2-C of CH_4 must be retrieved from the gas GWP based on the respective C mass weight in each gas. CH_4 -C: CO_2-C ~ 2.75 kg CO_2 embodied into one kg CH_4 to retrieve from fossil CH_4 GWP to get biogenic CH_4 GWP	Adapted source: ISO/TS 14067:2013
Greenhouse gas emission factor - GHG EF	Mass of a greenhouse gas emitted relative to an input or an output of a unit process or a combination of unit processes	Source: ISO/TS 14067:2013
Life cycle assessment - LCA	Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle	Source: ISO 14044:2006
Life cycle impact assessment - LCIA	Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product	Source: ISO 14044:2006
Life cycle inventory analysis - LCI	Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle	Source: ISO 14044:2006
Primary data	Primary data consist of actual site-specific data from the field or process site that describe the studied system. Primary data are needed to describe the foreground processes; the more primary data available, the	Own

	more reliable and useful LCA results. Primary data are usually collected through field surveys. In agricultural LCA, primary data consist of quantified information on field inputs, yields, fuel and water use, etc. NB: ISO 14067 differentiates site-specific from primary data, but for the sake of clarity in this report, primary data and site-specific data are assumed to be similar.	
Product category rules - PCR	Set of specific rules, requirements and guidelines for developing Type III environmental declarations for one or more product categories. PCR include quantification rules compliant with ISO 14044.	Source: ISO 14025:2006

1 Context

1.1 Study rationale

With the expected regulations in Europe on Green claims, it is anticipated that the coffee sector will need to develop appropriate Product Environmental Footprint methodologies. Much of the footprint is within control of the individual roasters, and the methodologies for calculating these footprints are well defined. The Footprint of Green coffee though, especially given the developing GHG Protocols, and the developing suite of tools linked to IPCC assumptions, appears more open to interpretation. Hence, green coffee carbon footprints vary greatly across published data.

Given the competitive nature of reporting on the impact of green coffee agriculture, ISIC and partners wish to define the most appropriate ways to handle the different aspects of the impact of green coffee, in such a way that the reporting is standardised and scientifically representative. Therefore, ISIC is seeking to commission a technical / literature review of the existing state of footprint data and studies covering coffee agronomy, analysed with the intent to then advise ISIC on where, given materiality, simplifying assumptions could be made. The review should define the minimum requirements needed to report on a **green coffee footprint** while retaining scientific credibility and should form a paper that could be published externally.

1.2 Scope of the review

The methodological review concerned all coffee production areas and systems without any restriction, but focused on a cradle-to-gate system stopping after the first transformation stage from cherries up to green coffee. Further transformation stages (*e.g.* roasting or packaging) were not included in the analysis and all data and approaches should consider impacts per unit of green coffee output.

For completeness, the study should assess all GHG emissions – not just carbon – and should not include the biogenic carbon removal from the coffee bean itself – as this is released through processing / consumption or disposal downstream.

The focus for this study was:

- to shed some light on contribution analysis outputs and inherent GHG impact hotspots according to the varying systems;
- to review underlying assumptions in various GHG accounting methodologies and their implications in terms of results sensitivity and uncertainty;
- to stress robust methodological approaches and parameters against knowledge gaps;
- to define the minimum reporting requirements to make valid judgements on the impact of coffee;
- to support the simplification of methodology development, while keeping the process of data capture as simple as possible, not the agreement on the specific data sets to then use.

The following GHG accounting aspects were specified as out-of-scope for this study:

- Reporting on Deforestation and historical land use Change
- Options for impact reduction
- Critique of specific tools used for reporting footprints
- Carbon Credit mechanisms

In agreement with the detailed target topics, the study encompasses in-depth critical reviews of:

- GHG accounting guidelines in agrifood systems with a focus on specifications for perennial crops (eg. GHG protocol, PAS 2050:2011, EU PCR, etc.) and allocation issues.
- Input-related field emission modelling (IPCC 2019 Tier 1, regionalised emission factors…).
- Biomass quantification of coffee trees and associated trees (review on allometric equations, planting density influences, etc.).
- Insights on biochar applications in coffee systems and observed field emissions.
- Insights on carbon stocks with regards to IPCC Tier 1 LUC modelling.
- Emission factors for waste management and composting (for both coffee residues, including pruned trees or mulch, and wastewater from wet processing).
- Background emission factors for fuel, energy carriers, irrigation equipment, transport, pesticides, etc.
- Contribution analysis of the various stages and processes along the life cycle from nursery (and background processes) up to green coffee.

The final outputs of all topic-specific reviews were articulated in the final report in order to:

- Reflect on most common discrepancies across methods or applications, and stress the best available choices from a scientific point of view;
- Emphasise on calculation parameters that have the most influence in the results in terms of both quantitative effect or uncertainty embedded;

Expected deliverables were as following:

1. A sound and detailed review of GHG accounting methodologies applied to agriculture with a focus on coffee and the great diversity of cropping systems.
2. A report on recommendations to streamline green coffee carbon reporting across the sector.

1.3 Methodology

The reviews were based on published articles as well as specific guidelines and reports. Reviewed topics were split among experts according to their respective fields of expertise. However, some competence overlapping also enabled some pairwise deepening and cross-checking on most critical issues. Experts worked together on the articulation of subtopics for the final report elaboration.

The system boundary of the study included all inputs and outputs from the upstream input provision to the plantation up to the final sorted unpackaged green coffee beans, *i.e.* a cradle-to-gate system (Figure 1). There was no a priori cut-off, and all processes should be included except for capital goods, which are commonly not accounted for in agricultural LCA due to their negligible impact and the lack of accurate inventories.

The process chain included the whole perennial plantation and three potential transformation routes for coffee cherries: 1) dry processing, 2) semi-wet processing, and 3) wet processing. According to the review scope, the determination of land use change prior to the plantation establishment was not investigated, as it was part of another complementary study. However, should LUC occur in a given socio-geographical context, related emissions and impacts should be included within the assessment. The methodological approach for LUC inclusion was hence further discussed in this report.

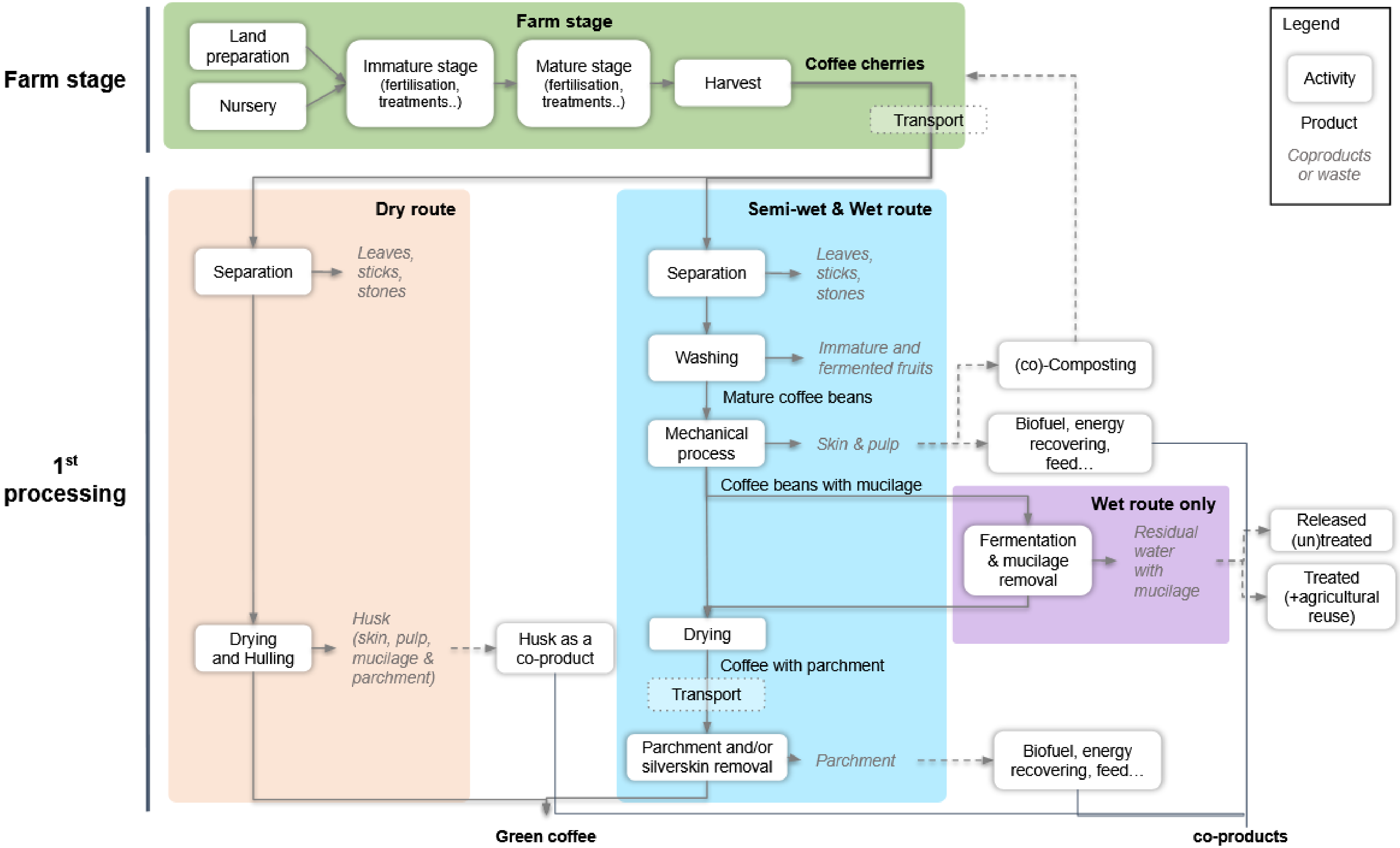

Figure 1. System boundary of the report: coffee farm + 1st processing stages. NB: ranking and sorting coffee beans to reach green coffee standard is supposed to be included in the study but not detailed in the figure given the lack of details across the studies (i.e. no data on actual loss rates or potential sorting machine use)

2 Review outputs

2.1 Review on published coffee carbon footprints

We conducted a narrative review of coffee LCA studies in the literature. The searches yielded 147[2], 172[3] and 285[4] articles and reports on the Web of Science, Scopus, and Google Scholar, respectively. We also added papers dedicated to carbon footprint analyses[5] and some primary studies extracted from reviews, which had not been identified through the database queries. More than 80% of the studies were published in the last ten years. Primary checks on search errors[6] and duplicates[7], led to a consistent corpus of 227 papers and reports. Then, publications were first filtered according to their goal and scope, and studies eliciting no specific system boundaries or coffee LCA results were discarded (76%). Most of those discarded studies i) did not display LCA coffee results but rather inventories, sustainability assessment indicators, non LCA-based water footprints, etc. (21%); ii) focused on technologies, processing or packaging only (18%), iii) were out of scope such as reviews on biomass or LCA recommendations (15%); or concerned recycling processes for coffee waste that entered the system with no environmental burden, *i.e.* not accounting for coffee production and processing (15%). Spent ground coffee, in particular, was the focus of many recent studies, *i.e.* about half of the studies published in 2022-2023. The rest of the studies related to coffee waste chemical analyses (3%), socio-economic aspects including consumers' view on LCA results (3%), or were inaccessible (1%). Second, an in-depth review revealed a further eighteen discarded studies because they were either partially inconsistent[8] or redundant[9]. We also could not further investigate two studies that only displayed endpoints and normalised results. The final corpus consisted of 34 examined studies.

The data collection grid included metadata on the studied countries, coffee species, farming systems and processing types. Impact indicators were recorded per functional units and sub-systems. Where necessary, results on impact indicators and contribution stages were extracted from figures using an online free tool. In some cases, we also re-calculated some results to harmonise the functional units, *i.e.* to convert acre- into hectare-based results or coffee drink- into volume or coffee weight-based results. The analysis was straightforward and did not require any statistical tools. Data exploration was carried out with R v.4.2.1 on R studio v.2023.06.2. We first analysed the consistency and liability of studies in methodological terms, notably, regarding the data representativeness and

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[2] coffee (Topic) AND lca OR “life cycle a*” (Topic) on August 14. 2023: https://www.webofscience.com/wos/woscc/summary/add2e1e3-4e94-4f86-9f80-d5b001810b88-63f4f04f/relevance/1

[3] coffee (Topic) AND lca OR “life cycle a*” (Topic) on August 14. 2023: https://www.webofscience.com/wos/woscc/summary/add2e1e3-4e94-4f86-9f80-d5b001810b88-63f4f04f/relevance/1

[4] "coffee lca" OR "coffee life cycle assessment" OR "coffee life cycle analysis" OR "lca of coffee" OR "life cycle assessment of coffee" OR "life cycle of coffee" OR "life cycle analysis of coffee" OR "life cycle analyses of coffee" in English only and without including references. The least relevant pages, i.e. the second half of output pages, were filtered manually on August 14. 2023.

[5] “coffee carbon footprint” OR “carbon footprint of coffee” in Google Scholar, 92 outputs viewed on August 14. 2023.

[6] Errors in the title, key word interpretation, not English, etc.

[7] Using a R script on DOI, with previous check on DOI record consistency.

[8] The most common source of error or uncertainty on the paper quality laid in the lack of explicit field emission modelling. In case of any doubt, we wrote to the authors to seek for clarification. When sufficient clarifications were given, studies were kept in the final corpus.

[9] In the case of Theses (Ph.D. and Master ones), whose parts were also published as articles or book chapters, we consolidated all needed information from the various sources and only kept a unique reference associated with a given dataset. We did the same in the case of proceedings’ papers further published as journal articles or articles from the same authors providing complementary information on unique LCA studies

scopes of the studies. Then, we investigated further the impact results and contributions. Finally, we stressed the main uncertainty sources and gaps to be filled, both methodological and scientific ones.

2.1.1 Overview of the covered coffee systems and LCA extents

2.1.1.1 Representativeness and variability of coffee farming systems

The data collection grid included metadata on the studied countries, coffee species, farming systems and processing types. Impact indicators were recorded per functional units and sub-systems. The great majority of reviewed studies (n = 25) investigated *Coffea arabica sp.*; 4 studies looked at *Coffea canephora sp.* Robusta; the remaining studies (n = 5) looked at both or did not specify; none investigated *Coffea liberica sp.* (Figure 2a). Although the dominance of arabica was relevant in the past, robusta global share is getting close to half nowadays. Hence, robusta and other species were underrepresented in the corpus. Central and South America was the most represented region with 73% of all studied systems (Figure 2b), including 18% and 16% for Colombia and Brazil alone; respectively (Figure 2c). This is aligned with this region representing about 70% of the global coffee production (Rega and Ferranti, 2019). Costa Rica and Vietnam were also presented in various studies. From the top five producing countries in 2020[10], only Ethiopia was not represented in our corpus. However, in some cases, the indicated countries of origin were not actually investigated. In Humbert et al. (2009), for instance, the focus was to compare the impacts of various coffee preparations while mixing coffee from Brazil, Colombia and Vietnam as main supplying producers. The theoretical systems relied on secondary data for the farm stage, whereby Brazil was assumed as a proxy for all considered coffee producing countries. Likewise, Hassard et al. (2014) used proxy data from Nicaragua to model their theoretical supply from Guatemala. Overall, a third of the studies did not use primary data for the farm stage and relied on existing published datasets; those were mostly the ones on Brazil by Coltro et al., 2006, *i.e.* 43% of studies based on secondary data. In these studies, the uncertainty on results was greater due to potential uncovered discrepancies between theoretical concatenated systems and actual practices in the field.

In terms of cropping system complexity, four main categories were covered: complex agroforest[11] (27%), simple agroforest (22%)[12] —also called by some authors “shaded monoculture”—, and full sun monoculture (27%) or polyculture (1%). The rest of the studies (23%) were either mixes of various systems or did not provide enough details on the cropping system types; those studies mostly used secondary data for the farm stage. Complex agroforestry encompasses here traditional polyculture, commercial polyculture and further not specified agroforestry coffee plantations. Simple agroforestry encompasses coffee systems with a single shade tree species. By definition, agroforestry is a broad concept whose baseline is the combination of crops, which can be both annuals or perennials, and

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[10] https://www.visualcapitalist.com/worlds-top-coffee-producing-countries/ on August 31. 2023, data source: International Coffee Organization

[11] Also called “Multistrata systems” In Cardinael et al.2018, Cardinael, R., Umulisa, V., Toudert, A., Olivier, A., Bockel, L., Bernoux, M., 2018. Revisiting IPCC Tier 1 coefficients for soil organic and biomass carbon storage in agroforestry systems. Environmental Research Letters 13, 124020. Adapted from Nair, P.K.R., Kumar, B.M., Nair, V.D., 2009. Agroforestry as a strategy for carbon sequestration. Journal of Plant Nutrition and Soil Science 172, 10–23. https://doi.org/10.1088/1748-9326/aaeb5f; https://doi.org/10.1002/jpln.200800030

[12] Also called “Shaded perennial-crop systems” In Cardinael et al.2018, Cardinael, R., Umulisa, V., Toudert, A., Olivier, A., Bockel, L., Bernoux, M., 2018. Revisiting IPCC Tier 1 coefficients for soil organic and biomass carbon storage in agroforestry systems. Environmental Research Letters 13, 124020. Adapted from Nair, P.K.R., Kumar, B.M., Nair, V.D., 2009. Agroforestry as a strategy for carbon sequestration. Journal of Plant Nutrition and Soil Science 172, 10–23. https://doi.org/10.1088/1748-9326/aaeb5f; https://doi.org/10.1002/jpln.200800030

trees. However, there are critical discrepancies among various agroforestry systems. In a traditional coffee agroforestry system also called "rustic" (van Rikxoort et al., 2014), natural forest is only partially cleared in order to keep existing native trees within the plot. On the contrary, in commercial polyculture, new trees are usually planted together with the coffee trees in order to provide specific benefits. Hence both the density, the age, and the type of associated trees matter when analysing agroforest diversity, as both imply different practices and overall plot performances. In the corpus, associated trees were mostly the focus of standing biomass estimation, and not much attention was paid to the interactions among crops and trees and how to account for associated ecosystem services and allocation issues within LCA. Only a few studies explicitly accounted for allocation ratios among associated crops (*e.g.* Basavalingaiah et al., 2022; Enveritas, 2023) or investigated complex outputs from agroforestry systems (*e.g.* Acosta-Alba et al., 2020, 2019).

For the first processing stage, the great majority of studies investigated wet processing only (55%) or together with dry processing (26%); 19% of the studies investigated dry processing only. Whether this processing was taking place on- or off-farm was not systematically specified but could be deducted from specific transportation details. Semi-wet processing was not explored in any reviewed study.

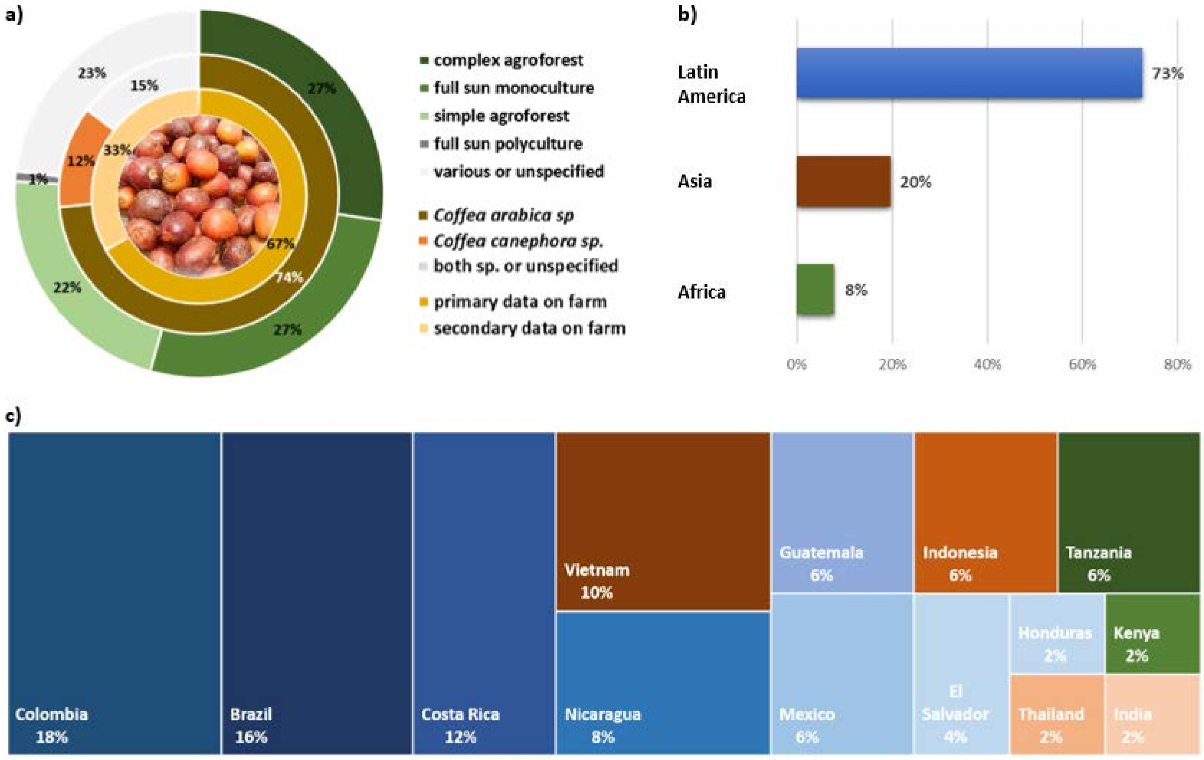

Figure 2. Overview of studied coffee systems and origins in the reviewed LCA and carbon footprint studies. a) by coffee species or cropping system or source of data b) by region c) by countries. All % are expressed as the percentage of the total number of studies of the final corpus of the review.

Very few studies considered the perennial cycle of coffee trees in the modelling of agricultural practices and related input-output fluxes. Most studies only gathered data for one year of productive coffee plantations. As shown in the literature, given the complex pluri-annual functioning of perennial plantations and delays in responses to environmental stresses or management practices, it is paramount to consider several consecutive years of production and to also integrate other development stages to average performances and impacts (Bessou et al., 2016, 2013; Cerutti et al., 2013). Bias in results may be critical particularly in studies relying on data collected in the field for a reduced number of plantations and over short periods of time (*e.g.* Quack et al., 2009), as well as in those comparing contrasted cropping systems (*e.g.* Brenes-Peralta et al., 2022). Such a bias would be less critical in studies covering several years (*e.g.* Noponen et al., 2012) or covering large samples, whereby regional disparities in practices and performances along the crop cycle may be geographically averaged (*e.g.* Enveritas, 2023).

There were a few exceptions, though, with some more systematic and holistic studies (*e.g.* Acosta-Alba et al., 2020; Brenes-Peralta et al., 2022; Rahmah et al., 2023; Trinh et al., 2020). In Trinh et al., 2020, data inventory was detailed by plantation stage. When focusing on yields, which directly influenced the impact indicators as being the FU common denominator, it was interesting to note that yields in green coffee (t/ha) were on average 18-21% higher during the 21 years of full production compared to the computed yields over the whole cycle of 30 years. Contrarily, yields during the first 6 and last 3 years were on average 2.4 and 1.8 times lower than those during full productive years and the averaged cycle; respectively. Depending on the year for the data collection and the age of the plantation, those differences in yields over the whole crop cycle would have affected the LCA results if calculated without integrating the whole cycle. Moreover, those differences might vary across compared systems, emphasising the consequent bias in the results. In the exemplified study, variability in yields along the whole cycle was smaller in the conventional intensive system compared to the two others (Trinh et al., 2020).

Representativeness is a key data quality attribute in LCA because it defines how well-adapted the data is to fulfil the study objectives. In agricultural systems, all dimensions of representativeness matter, including the geographical, temporal and technological ones, since management practices are highly dependent on the local contexts and can greatly vary. Table 1 lists some of the main agronomic parameters gathered from the reviewed studies. High standard deviations indicated a great variability in all parameters within the sample, in particular for nitrogen (N)-based fertilisers and green coffee yields. Seven studies considered irrigation in coffee plantations but very little detail was provided and did not enable to analyse the diversity of irrigation systems and their impacts.

Table 1. Variations in key agronomic parameters across reviewed studies (both coffee species were considered together and results are displayed as they appeared in the studies, hence there is no linear relationship between outputs in the table)

Parameter	***Mean***	***Median***	***Min***	***Max***
Planting density (coffee trees/ha)	4 067 (±41%)	4 500	150	10 000
N fertilisers* (kg/ha)	215 (±72%)	177	0	1152
Fresh coffee cherry yield (kg/ha)	5 288 (±51%)	4 800	628	13 605
Parchment coffee yield (kg/ha)	1094 (±56%)	1 032	126	2 387
Green coffee yield (kg/ha)	1419 (±79%)	1 064	373	5 386
Irrigation (m^3/ha)**	3 103 (±45%)	3 458	1 124	4 940

*Not all studied displayed the detailed amount for each fertiliser types nor the N content of organic amendments applied. Total N fertiliser estimates are likely underestimated. Standard deviations to the means are given in brackets. ** Focusing on irrigated systems only (n=14)

The least detailed practices at farm level were related to crop residues and organic amendments. Crop residues on coffee farms may come from two main sources: the coffee itself and the associated crops or trees. Coffee residues consist of both leaf litter and pruning residues within the plantation and coffee residues from processing (*e.g.* coffee pulp, husks, parchment, etc.). Leaf litter and pruning residues may account for 5 to 12 t/ha depending on both coffee and shade trees densities (Van Rikxoort et al., 2013). Further crop residues may be brought from other plots or farms as organic amendments. Likewise, coffee plantation residues may be exported or recycled (such as pruning wood used for fences or fuel wood), although those scenarios were not discussed in the coffee studies, apart from the two bioenergy dedicated studies by the same authors (Aristizabal-Marulanda et al., 2021; Aristizábal-Marulanda et al., 2021). The amounts and management types of crop residues and organic amendments may significantly influence the coffee performances, both in terms of agronomic outputs and environmental impacts. Depending on the type of organic matter and how it may degrade, ferment or be stabilised (*e.g.* by composting), emission types and amounts will vary. According to IPCC (2006) as implemented in the Cool Farm Tool, residues left in heaps or pits would emit 33 times more CO_{2eq} than when used as mulch in the field due to anaerobic conditions leading to potent GHG such as N_2O and CH_4, while biogenic CO_2 from aerobic decomposition is considered as neutral. Very few studies recorded precise information on residues and none of them inventoried all potential residues and their fate. For instance, Enveritas (2023) inventoried coffee leaf litter and husks; Rahmah et al., 2023 compared scenarios with and without field application of coffee pulp.

2.1.1.2 Goal and scope of coffee LCA studies

Across the reviewed studies, various plantations and processing routes were covered, except for semi-wet or honey coffee, hence not displayed on the figure. As for the farming stage, about one third of the studies did not use primary data for the processing stages. The wet process route was most represented across the studies (67%), in accordance with arabica being the most studied species and the one mostly prone to wet processing.

In terms of system boundaries, about a third of the studied systems included the consumption of the coffee drinks, mostly comparing at least three preparations. Moreover, some studies presented results both at farm or processing-plant gate and after consumption, which provided results for 234 systems in total. For the purpose of this report, only sub-systems up to the green coffee were further considered, *i.e.* 141 results including 76 at farm gate and 65 at mill or import harbour gates.

Surprisingly, two studies defined the functional unit as kg green coffee, although those included secondary transformation and coffee consumption. Those results expressed per kg green coffee would be misleading, especially if extracted from the studied contexts and compared on the same functional unit basis but with different system boundaries. They were hence not included in the review. To a lesser extent, the common use of the “green coffee per hectare” metric may be confusing as hectare most commonly refer to outputs from the field without including any processing stage, although green coffee embeds first processing to transform cherries into commercial coffee beans. Finally, none of the reviewed papers specified the moisture of the coffee functional unit. At global level, green coffee moisture only varies between 10-14% as moisture level of exported green coffee is standardised. However, variation in this parameter could matter when comparing studies, as cumulative losses, in weight (through moisture) or actual quantities, along the chain would linearly affect the impact indicators per output unit. Generally, functional units should be more specific and better reflect the goal and scope level of the studies. The key steps of system boundaries and functional unit definition are recalled in Section 2.2.

None of the studies included capital goods, which is in line with commonly used guidelines for agricultural production such as PAS2050 (BSI 2011), as justified by some authors. Capital goods are unlikely to contribute significantly to any impact unless focusing on the coffee machine production, which was the focus of a few LCA studies that were disregarded in this review as they did not include the coffee farm stage. It might be relevant to investigate those studies further in order to double check whether detailed LCI on machines and transformation infrastructures would lead to further discrepancies between coffee drinks prepared with various technologies.

A great majority of the studies (82%) did not consider or mention any co-product allocation. Among the remaining studies, there were three studies without primary data on the farm stage and relying on background database including system expansion for waste management and energy recovery; two studies from the same authors focusing on downstream energy production from cut stems by applying mass allocation between coffee and stems, then substitution; and two studies applying economic allocation between coffee and associated crops in the same plot. Given the diversity of systems, including numerous agroforestry plots, and the potential diversity of coffee co-products, notably highlighted by numerous discarded studies only looking at coffee waste valuation (*e.g.* spent coffee ground), the lack of an in-depth investigation on co-products stressed potential gaps in accounting for the specificities and discrepancies across coffee supply chains. How should co-products be handled in LCA-based studies is recalled in Section 2.2.1.

2.1.1.3 Impact assessment methods

Concerning the global warming impact, not all studies relied on the same IPCC versions for the characterisation factors. Most single-issue or full LCA studies based on RECIPE 2008, CML 2001, TRACI 2008 and ILCD 2011, as well as studies using Cool Farm Tool v1., relied on 100-year global warming values from the fourth Assessment Report (IPCC, 2007). The other full LCA based on RECIPE 2016 and Usva et al., 2020, relied on 100-year global warming values from the fifth Assessment Report (IPCC, 2014). The discrepancies among both versions would be mostly critical for biogenic methane emissions from wastewater treatment, since global warming potential varies from 25 to 34 kg CO_{2eq}/kg CH_4 with feedback. No study used the versions from 2021, where discrepancies for N_2O global warming potentials would have also mattered.

2.1.2 Global warming impact results

2.1.2.1 Overview of impacts

Global warming impact indicators varied greatly across studies depending on the system boundaries, but also within similar system boundaries. A summary of key results on global warming impact indicators is given in Table 2. At the different system boundary levels, both published and adjusted results are listed. Adjusted results concerned the units only in order to adjust the results to the actual system boundaries but did not include further harmonisation in the calculations (*e.g.* no harmonisation of field emission models used). Adjusted results combined results for parchment and green coffees at mill gate (based on the 1.25 ratio) and differentiated with or without land use change (LUC).

Table 2. Numbers of studied systems for which at least one impact indicator is provided and overview of global warming impact indicators. Notes: LUC=Land Use Change; FU=Functional Unit

Total count = 141	***Cradle-to-farm gate without any transformation***	***Cradle-to-1st processing gate (on- or off-farm)***
Studied systems (count)	**76**	**65**
Studied system counts by functional unit	1 ha.yr: **42** 1 acre.yr: **3** 1 kg coffee cherry: **31**	1 kg green coffee: **45** 1 kg parchment coffee: **14** 1000 USD.ha outputs: **3** 1 ha*.yr: **3**
Averaged coffee product ratios	cherry kg/ha: **5,288** (±51%)	cherry/parchment: **5** cherry/green: **5.7** (±19%) parchment/green: **1.25**
Published global warming impact range: min-max (kgCO_{2eq})	per ha.yr: **-9 960 to 102 330** per kg fresh cherry: **0.03 to 1.82**	per kg green coffee: **0.15 to 10.52** per kg parchment coffee: **3.10 to 11.61** per 1,000 USD.ha outputs: **1500 to 3 500** per ha.yr: **6 400 to 8 700**

Total count = 141	Cradle-to-farm gate without any transformation	Cradle-to-1st processing gate (on- or off-farm)
Adjusted FU- global warming impact range (including differentiation between with or without LUC): min-max (kgCO_{2eq})	per ha.yr (with LUC): **-9 960 to 102 330** per ha.yr (without LUC): **109 to 10 220** per kg fresh cherry (with LUC): **none** per kg fresh cherry (without LUC): **0.03 to 1.82**	per kg green coffee** (with LUC): **1.63 to 10.52** per kg green coffee** (without LUC): **0.15 to 14.51**

Notes: 1st processing includes post-harvest operation up to drying (final grading and sorting may or may not be included as not specified in the studies).
*Results expressed at mill gate per ha.yr may be confusing since no processing is usually included at the ha level. Results expressed at mill gate per ha.yr and USD.ha were also available per kg green coffee and are therefore only provided in this latter FU in adjusted results to avoid confusion (n=65 => n=51)
**Conversion of parchment into green coffee embodied uncertainty related to both the ratio and an underestimation of added potential impact from parchment hulling.

2.1.2.2 Green coffee main impact contributors and discrepancies

Focusing on the green coffee production, the discrepancy across results could be critical especially when switching from positive to negative global warming impact indicators, at the hectare level, with carbon storage due to LUC. Overall, four studies investigated LUC and four others considered some biogenic carbon storage in the coffee plantations without modelling any LUC. Biogenic carbon stored in plantations, within coffee or other trees, should not be included in the carbon footprint as specified by the guidelines (*e.g.* PAS2050, GHG Protocol, etc.) unless considered within a proper long-term LUC modelling. Carbon storage in any stand may be accounted only in relative quantities compared to previous stands and providing that a consistent time frame is aligned with a minimum time-averaged storage (at least over 20 years according to IPCC recommendations). Across the reviewed studies, negative global warming impacts, such as in Noponen et al. (2013), might have resulted from distorted LUC modelling or inconsistent biogenic carbon accounting. Distortion might be due to varying choices across studies in terms of time parameters. Inconsistent biogenic carbon accounting might be due to flaws in the extrapolation of carbon stock changes or imbalanced accounting for carbon storage and release in LUC contexts. Although net benefits from LUC are possible in some given contexts, such cases were not thoroughly assessed in the reviewed corpus. In Noponen et al. (2013), carbon stocks were estimated and amortised over 9 years due to experimental constraints. The consensual time frame for carbon estimates is at least 20 years, therefore the LUC modelling in Noponen et al. (2013) might be distorted compared to other studies and those results were not further discussed.

According to the remaining studies, the global warming impact indicator of green coffee following land use change to establish the plantations varied from 1.63 to 10.52 kg CO_{2eq}/kg green coffee (based on IPCC 2006 Tier 1 for LUC modelling). LUC contribution to the final global warming impact ranged from 1%[13] to 75%, hence leading up to a four-fold impact increase. LUC contribution is usually quite critical in agricultural LCA, particularly in the tropics where rainforest may be converted into

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[13] In this study, LUC contribution was averaged over a whole region including thousands of farmers, among whom very few would mention any LUC. The authors specified that the modelled LUC was very likely underestimated and would require a more in-depth investigation (Enveritas, 2023).

agricultural land. It can hence lead to significant differences between coffee systems given contrasted local development contexts and LUC history. The overall global warming impact indicator of green coffee with or without LUC varied between 0.15 and 14.5 kg CO2eq/kg green coffee, with a median value at 3.6 kg CO_{2eq}/kg green coffee (Figure 3).

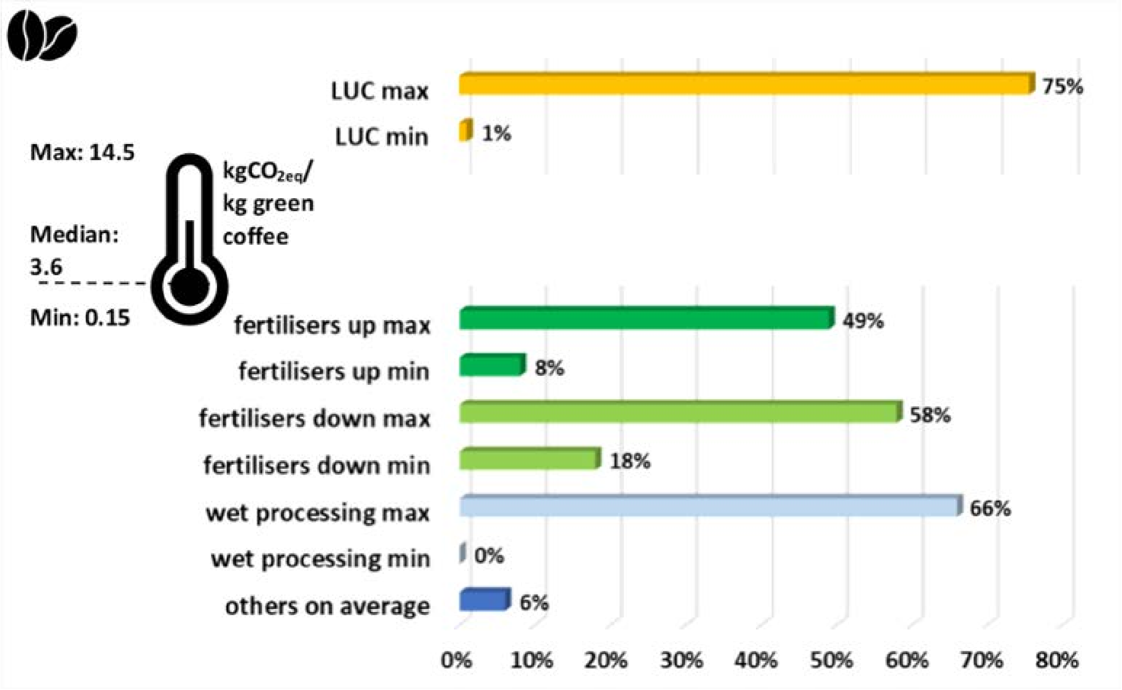

Figure 3. Overview of global warming impacts and main contributors at cradle-to-mill gate (1st processing). All % are expressed as the percentage of the global warming impact. Notes: Green coffee is averaged for both dry and wet processing routes. Coffee icon from Muhammad Nur Auliady Pamungkas (beans), Noun Project CCBY3.0

LUC apart (studied systems, n=51), overall main contributors to the global warming impacts of green coffee production were synthetic fertilisers with a median contribution for both fertilisers upstream (manufacture and transport) and downstream (field emissions) together of 66% (Figure 3). In studies providing disaggregated information, greenhouse gas emissions from fertilisers upstream contributed to 8-49% of the impact (median value at mill gate: 20%), and those from downstream emissions to 18-58% (median value at mill gate: 37%).

The second main contributor was wet processing where both energy for processing and emissions from anaerobic treatment of wastewater could contribute to GHG emissions. Fermentation emissions related to wet processing were not consistently modelled across studies, which raised a critical issue as they were quite significant contributors, from 27% to 66% of the global warming impacts (Killian et al., 2013; Maina et al., 2016; van Rikxoort et al., 2014; Van Rikxoort et al., 2013). In the end, this contribution was highly variable and uncertain across studies. Some studies did not include emissions from wet processing due to a lack of data or with no disclaimer (*e.g.* Brommer et al., 2011; Quack et al., 2009; Vera-Acevedo et al., 2016; Rahmah et al., 2023). In comparison, emissions from dry processing and other post-harvest operations up to green coffee were negligible. Drying was mostly in the sun and hulling only contributed to 1-2% when disaggregated from other post-harvest energy-related contributors.

The third main contributor were N_2O emissions from residues, albeit those emissions were not systematically considered and led to quite contrasted contributions. Overall, only seven studies considered emissions from residue decomposition in the field and contribution varied from 4% in Maina et al. (2016) up to 90% in Jaramillo et al., (2017). In Noponen et al. (2012, 2013) emissions related to residue decomposition contributed between 9 to 42% of the global warming impacts across systems. Crop residues in Maina et al. (2016) were not detailed. In the other studies, all considered coffee leaf litter, but only four also considered coffee pruning as well as litter and pruning from associated trees (Noponen et al., 2012, 2012; van Rikxoort et al., 2014; Van Rikxoort et al., 2013). Finally, only one study also accounted for emissions related to coffee husk decomposition, *i.e.* Enveritas (2023). The median contributions for those residues across these studies were 11% and 14% at mill and farm gate (no transformation), respectively.

Besides those main contributors, the respective contributions of fuel for transport (median contribution of 3% at mill gate) or field operations (median: 2% at mill gate); pesticides upstream emissions (median: 5% at farm gate) or irrigation were less critical. Only 15% of the studied systems included irrigation (in 7 studies) and only three studies provided some details on its global warming contribution, which was highly variable between 4% and 31% at mill gate. The results on irrigation contributions were unlikely to be representative of contrasted types and intensities of irrigation across coffee farming systems and are not further discussed.

2.1.3 Uncertainty sources and data gaps

LUC apart, at the plantation level, despite some mentions of quite complex coffee systems, such as agroforestry plots, little attention was paid to consider this complexity and potential allocation issues within the impact assessment. Figure 4 shows no clear-cut difference in the global warming impacts based on the cropping system type and large variabilities within system types. This may be partly due to the fact that, when discarding LUC, the cropping system type among the displayed categories may not significantly affect the carbon footprint compared to other main contributors such as fertilisers (*e.g.* Noponen et al, 2012). However, part of the effects may also be missed due to incomplete descriptions and modelling of the diverse system structures and functioning. Some studies estimated carbon stock in associated shade trees but did not investigate how competitions for resources may affect inputs/outputs among crops and trees. Apart from a few studies mentioned before, there was a lack of a clear systemic delineation between coffee and associated plants in the case of agroforestry plots.

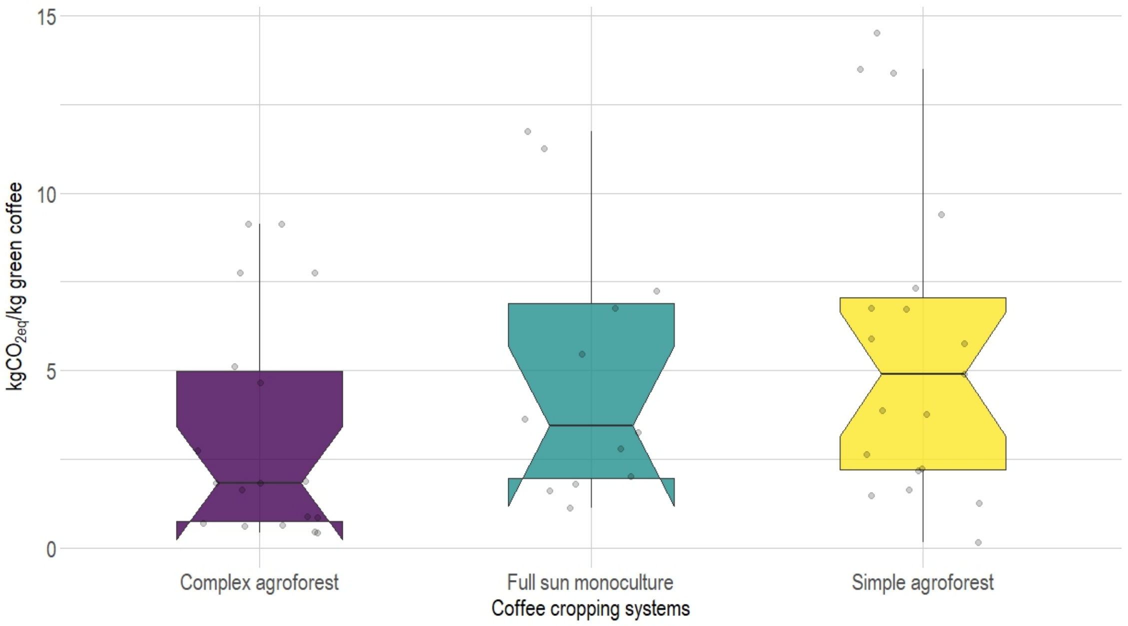

Figure 4. Green coffee global warming impact according to cropping system types (cradle-to-1st processing gate, no LUC considered, n=49, no result available for the 1% Full sun polyculture for this system boundary).

Besides, the overall balance in inputs/outputs should also include the residues from coffee and potentially other associated crops or trees, should the latter be considered within the system boundary. Inclusion of residue emissions clearly affected the final global warming indicators (Figure 5a). More attention should be paid to quantify on-farm or off-farm residue decomposition and emission profiles properly, so as to make sure that the quantification of emissions is complete, as well as to check whether synthetic fertilisers were or could be substituted. Many studies focusing on coffee co-products or waste could provide insights on quantities and properties of those residues to derive a more systematic accounting (*e.g.* Catalan et al., 2019; Cruz, 2014; Dadi et al., 2019).

The added emissions of first processing were also highly variable and questionable (Figure 5b). The clear cut between dry processing for arabica or robusta may rather relate to differences at farm stage as dry processing would not be significantly different depending on the coffee variety. The clear cut between dry and wet processing for arabica is due to large variabilities and uncertainties in the modelling of both coffee supply chains. It stresses the likely underestimation of emissions and impacts from the wet process, as not all studies included wet process emissions nor used the most updated GWP for biogenic CH_4. Emissions from wet processing depend on many factors that can be highly variable but mostly depend on the amount of water used for washing and fermenting. The origin of water may also affect the energy-related emissions for pumping. In the end, the amount of emitted CH_4 is related to the wastewater amount and treatment that differ widely among geographical contexts and applied processes. Traditional fully washed processes use up to four times as much water compared to processes that reuse water (Van Rikxoort, 2011). CH_4 emissions, when included, were mostly based on IPCC coefficients for wastewater treatment but there was a lack of information across the studies on the overall process; *i.e.* detailing the origin of water, the amount of water used, the duration of the whole process, which influences fermentation outputs, and the type and duration of wastewater treatments. More data and knowledge would be needed to decipher the proper emission profiles of wet processes according to their specificities. Moreover, when wastewater is not treated and directly discharged into the environment, which may limit the CH_4 emissions, other pollutants may also become an environmental threat (Beyene et al., 2012; Blinová et al., 2017; Chanakya and De Alwis, 2004).

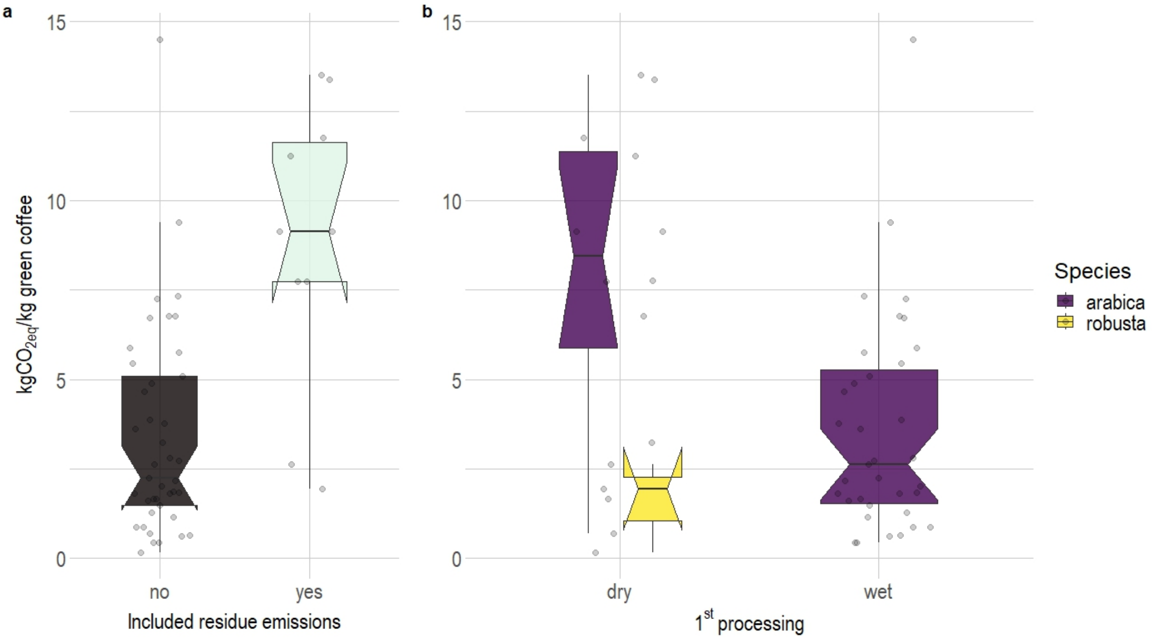

Figure 5. Global warming impacts of green coffee depending on the accounting for emissions from (a) residues: yes/no (n=51); and (b) the type of first processing: wet/dry (n=50) (cradle-to-1st processing gate, no LUC considered).

Although fertilisers-related field emissions were explicitly modelled across the studies[14] (mostly based on IPCC 2006 and derivatives), there was still a lack of transparency and details. Apart from a few studies (*e.g.* Noponen et al. 2012, Maina…), most studies did not specify if indirect N_2O emissions or CO_2 field emissions related to urea and liming practices were accounted for. Moreover, not all studies provided a detailed inventory on inputs, notably on fertiliser types and amounts, nor systematically differentiated between synthetic and organic ones. The variability among studies with no details available spanned a larger range than that of the other studies (Figure 6). Hence, the lack of transparency and details hampered a clear analysis of correlations. When analysing results per class of N-fertilisers, we could not identify any clear trend[15], despite residues and impact of 1st processing being split in order to try and disentangle the many factors. Figure 6a,b first show an extreme variability across all classes of fertiliser intensity and no clear cut between fertiliser managements. Some low-input systems had large emissions and vice versa. Those managements embed many factors that could not be fully discriminated against due to the lack of details available. In particular, the difference in organic versus synthetic fertilisers played a key role in some fertiliser-intensive systems as upstream emissions from organic fertilisers were much lower than those of synthetic ones, while fertiliser upstream emissions were significant contributors (*e.g.* Noponen et al. 2012). Finally, large discrepancies in wet emissions modelling may have also smoothed out part of the comparative results

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[14] It should be noted that it was a robustness criterion to actually retain a study.

[15] N-fertiliser classes were defined in order to yield comparable sample sizes across classes. The in-depth analysis revealed further doubts on some results that might not be fully consistent with the fertiliser doses displayed.

across fertiliser-classes, as exemplified in the >334 N class where wet process coffee supply chains had a lower impact than dry process coffee supply chains, which had a similar median impact as for the other N classes with wet processing.

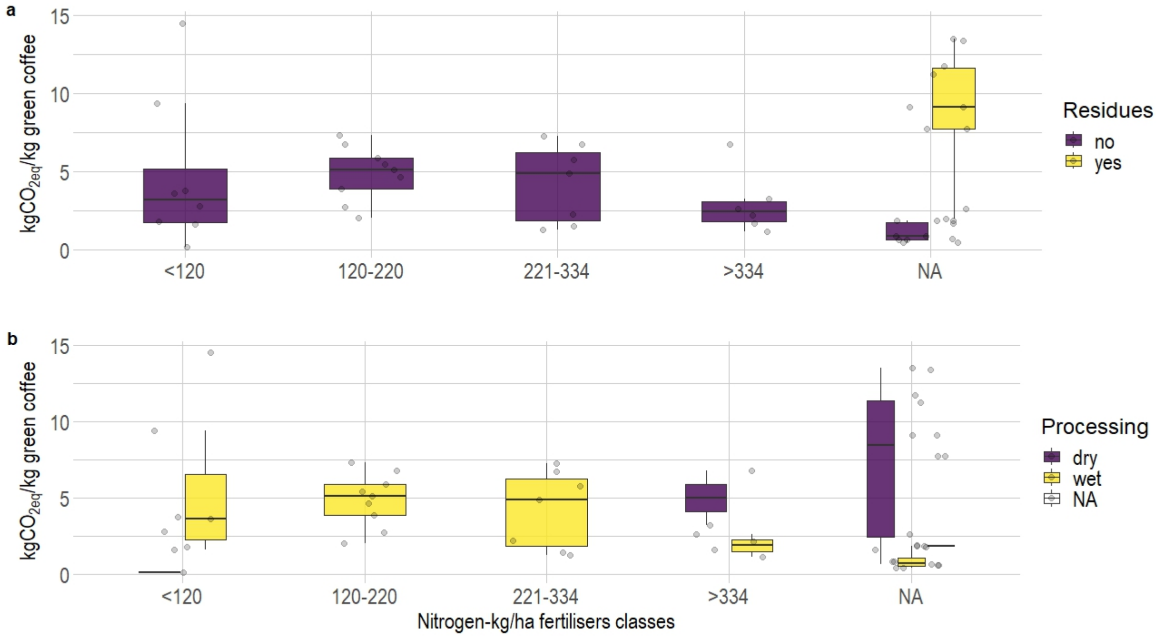

Figure 6. Global warming impacts of green coffee by N-fertiliser classes and depending on the accounting for emissions from (a) residues: yes/no; and (b) the type of first processing: wet/dry (cradle-to-1st *processing gate, no LUC considered, n=51).*

In conclusion, more information and data, as well as a more harmonised accounting, is needed to cover better emissions and impacts from coffee plantations. A more systemic approach is needed to grasp the complexity and variability of coffee supply chains at both crop and processing levels. The plantation complexity influences the biomass stocks, within the frame of LUC accounting, the ecosystem functioning and input/output flows, as well as the co-products and residue emissions over the whole perennial cycle. Post-harvest emissions also are critical and there is still a gap in knowledge and primary data to characterise processing emissions as well as to properly quantify losses along the supply chain.

2.2 Review on carbon footprint guidelines and harmonised parameters

We reviewed the key methodological guidelines applied to LCA and carbon footprint. These guidelines are internationally recognised as fundamental to ensure the reliability of results. After the first life cycle assessments in the early 1980s, LCA gained more traction in the 1990s with the development of bioenergy. However, at that stage the lack of harmonisation in the methods led to confusing results, varying upon the methods applied more than the data used, as highlighted in a seminal publication by Farrell et al. (2006) looking back at contradictory corn ethanol LCA studies. This confusion called for an unprecedented international harmonisation regarding environmental assessment, particularly through the structuring and formalisation work led by SETAC[16].

Since the early 2000s, LCA has become a standardised conceptual and methodological framework under ISO series 14040 (2000–2006). It is based on two fundamental principles. First, environmental impacts are quantified throughout the supply chain or ‘life cycle’, from raw material extraction (‘cradle’) to end-of-life of the product or service (‘grave’). Then, the impacts are quantified with respect to a functional unit, either a product quantity (one kilo, one car, etc.) or a usage or service (hours, kilometres, etc.). In that way, the environmental impacts of systems producing a similar function can be compared. Thus, LCA has become the worldwide standard for implementing environmental product declarations (ISO 14025:2006 Type III Environmental Declarations). ISO standards were defined, and translated into various languages, in order to make sure these fundamental principles and steps in application are commonly respected. They are regularly reviewed.

Further 14000 series ISO standards were developed, notably the ISO 14067 (2013) with relation to single issue LCA focusing on global warming assessment or carbon footprint. Besides, further guidelines were derived from the seminal ISO standards to provide sector wise declinations and practical information also called Product Categories Rules (PCR).

The Carbon Footprint Product Category Rules (CFP-PCR) for the assessment of the greenhouse gas emissions of UN CPC 01610 (Green coffee) has expired in 2016, but was considered as a central guideline in this review for two reasons:

- This is (was) the most accurate and specific standard in terms of impact (Global warming, also called Carbon footprint) and system studied (Green coffee)
- The ISO 14067 states “**where relevant PCR or CFP-PCR exist, they shall be adopted**”

Hence the use of the CFP-PCR (2013) as a first entry point, then complemented with the other standards when relevant.

In summary, the chosen key methodological guidelines, in the case of coffee carbon footprint, were the following (Figure 7):

- CFP-PCR (2013): Carbon Footprint of a Product – Product Category Rules for the assessment of the greenhouse gas emissions of Green coffee
- ISO 14067 (2013): an adaptation of ISO 14040 and 14044 to carbon footprint specificities
- LCA derived specific guidelines for food and perennials: PAS 2050:2011 (BSI 2011) and PAS 2050:2012 (BSI 2012) for horticultural products.

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[16] SETAC: Society of Environmental Toxicology and Chemistry, one of the most important international scientific organisations dealing with structural issues of life cycle assessment.

- Product Category Rules (PCR) for Moka[17] and Espresso[18] (International EPD System 2019 and 2018): partially analysed, because relying on CFP-PCR for green coffee.

The CFP-PCR for green coffee (2013), the PCR for Moka and Espresso have also expired, but they were still considered partially. The various coffee CFP-PCR would need to be updated.

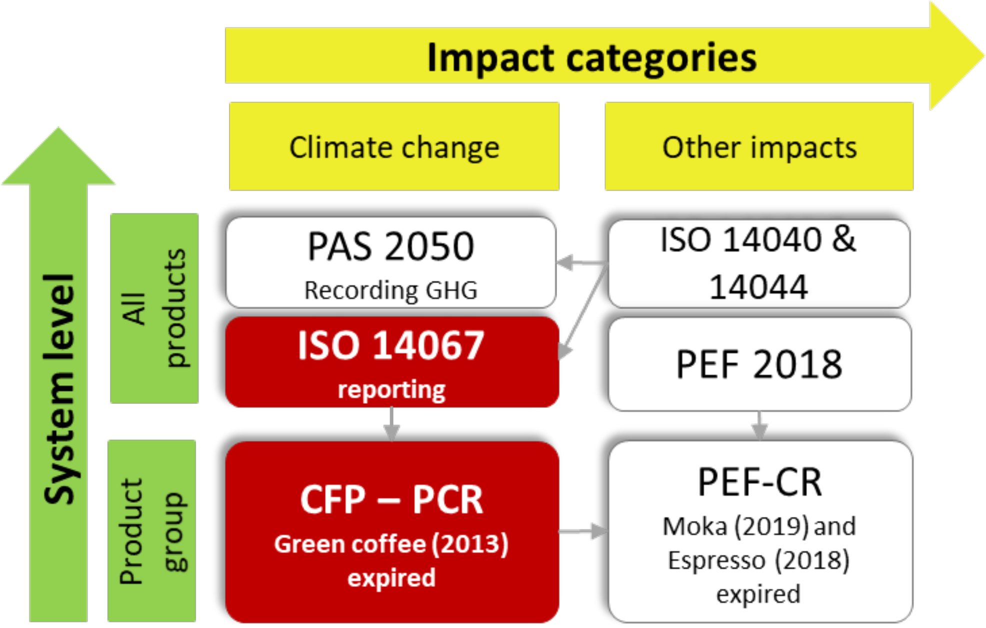

Figure 7. Key carbon footprint methodological guidelines analysed in this review: CFP-PCR for green coffee (2013), ISO 14067 (2013) and PAS 2050 (Including PAS 2050:2011 (BSI 2011) and PAS 2050:2012 (BSI 2012)), and their relation with guidelines addressing other impact categories: PCR for Moka and Espresso (International EPD System 2019 and 2018), and LCA standard ISO 14040 and 14044. Guidelines highlighted in red were considered as the most comprehensive baseline.

The review aimed at stressing both i) the minimum reporting requirements to make valid statements on the impact of coffee; and ii) stress robust methodological approaches and parameters against bottlenecks or knowledge gaps.

Key principles of a Carbon Footprint are based on the Life Cycle Assessment methodology (mostly described in ISO standards 14040 and 14044: Life cycle perspective, functional unit, iterative approach, relevance, completeness, transparency. Therefore, all guidelines follow more or less extensively the ISO stepwise methodology, which structures this section; *i.e.* 1) Goal & scope definition, 2) Life Cycle Inventory (LCI), 3) Life Cycle Impact Assessment (LCIA), and 4) Interpretation, reporting and communication.

2.2.1 Goal and scope definition

The goal and scope definition should ensure that the system boundary is explicit and consistent with the objective of the study. The goal of the study is embodied in the chosen functional unit that determines the proportion of all inputs and outputs relative to the reference flow aiming to the provision of the functional unit. For a given product, *e.g.* green coffee, the goal and scope of the study may vary depending on the temporal, geographical and technological scopes. As LCA integrates various

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[17] EPD System (2018). PCR 2018:03 Espresso coffee, version 1.01 (UN CPC 23912).

[18] International EPD System (2018). PCR 2018:03 Espresso coffee, version 1.01 (UN CPC 23912).

processes taking place at different locations and time points, it represents a snapshot of a product system, whose validity is limited to the defined scope. Besides the "mere amount" of a functional unit (*e.g.* 1 kg green coffee), details on its scope should be provided when introducing the study goal and scope (*e.g.* 1 kg green coffee provided at farm gate by X on average in 2020 - see recommendations below). Therefore, it is important to bear in mind that LCA results for a given functional unit may vary due to variations in the scope that may not be properly considered or elicited within this functional unit.

The scope of the system boundary is adjusted through an iterative process, whereby all processes and flows should be first considered and only discarded if it can be demonstrated that their contributions are negligible or below a defined cut-off. Transparency is a key principle and all assumptions and decisions along the LCA stages need to be made crystal clear and justified.

The final LCA results should be interpreted in light of adequacy of the system boundary to the study goal and scope, as well as the quality of data used relative to the study scope (*e.g.* data on Brazilian arabica coffee may not be suitable for a study in another country, also commonly found in the literature).

The CFP-PCR (2013) - further referred to as CFP-PCR only - recommends a description of the production system (organic, polyculture, monoculture…) and the number of trees per hectare for coffee trees (distinguishing Robusta from Arabica) but also for other trees in the case of polyculture.

Functional Unit

A proper FU should address the "what," "how much," "how well," and "how long." The quality of products is not considered in some of the PEFCR (Pedersen-Remmen 2022). For green-coffee, the CFP-PCR recommends: 1 kg of Green Coffee at 11.5% moisture delivered to port of origin or the roaster's warehouse if processing domestically. As recalled before, it is paramount that the FU reflects the study goal and scope and vice versa.

System boundaries

Green coffee carbon footprint can either be from cradle to the 'port of origin' or from cradle to the warehouse of the domestic roasting facility studies. A sub-system at farm gate can be found in the literature, notably when first processing takes place on-farm. However, it may be confusing as further stages up to green coffee, such as processing or final coffee grading and sorting usually go beyond the farm. The inclusion or not of such final stages and potential intermediary transports should be specified and reflected within the study goal and scope and the functional unit.

It is usually more efficient to list all the included stages and processes, rather than trying to make an exhaustive list of excluded ones. Based on past experience with agricultural and coffee-specific LCA no relevant processes, the CFP-PCR provides a summary of activities that should be covered:

- All relevant upstream processes of inputs into the green coffee production (including agricultural inputs, transport and raw material use);
- Energy use during production and post-processing;
- Transport of input materials, during production and post-processing;
- Packaging materials and processes;
- Repackaging, storage facilities and loading during post-production and at the port of origin.

A common exclusion in agricultural LCA are the capital goods. All reviewed standards agree that capital goods are to be excluded. Capital goods are input to the system, such as machines or buildings, with a lifespan greater than 3 years (CFP-PCR). Conversely, any input/consumable whose lifespan is less than or equal to 3 years should be included. For instance, irrigation pump manufacture may be excluded but not the manufacture of irrigation pipes that may be changed regularly (if their lifespan is less or equal to 3 years). The impact of such capital goods is usually negligible due to their long lifespan (more than 20 years for most infrastructure) and large throughputs, whereby only a negligible amount of their total impact would be allocated to the functional unit (equivalent to a small proportion of the total throughput over the complete lifespan). Only the manufacture and installation of such capital goods are excluded. Impacts related to their daily use and regular maintenance are included in the LCA in proportions to their use to fulfil the functional unit.

Another common exclusion is human energy inputs (CFP-PCR). The main reason is the difficulty to allocate human caloric expense to a given functional unit considering other daily activities and the great variability of individual metabolisms and labour costs.

Cut-off rule

Although simple by essence, the cut-off rule is a fuzzy concept in LCA because it applies at system boundary stage but should be based on quantified information further down the LCA calculations. Cut off rule varies slightly between standards. At least 95% of climate change potential associated with the declared unit shall be included according to the CFP-PCR. The same cut off value is used in the PAS2050, where it is specified that the cut-off applies to the *anticipated GHG emissions and removals.* It indeed raises the question of how to accurately anticipate (<5% error) all contributions without actually making a full inventory. In the PCR for Moka, it is specified that the cut-off should be checked based on a combination of expert judgement and a sensitivity analysis demonstrating how the un-investigated input or output could affect the final results. But this latter sensitivity analysis requires to be able to still quantify the cut-off flows. Besides, the PCR for Moka sets a higher cut off value with a minimum of 99% of the environmental impacts that shall be included. In practical terms, decisions on cut-offs should be adjusted along an iterative process. Where cut-offs are as low as 1-5% and need to be justified on quantitative analyses, they do not translate into an actual criterion to reduce the LCI workload.

LCA scope and sampling approach

The scope is quite critical in agricultural LCA, as agricultural systems are much less homogeneous than industrial systems (for which LCA was originally developed). The scope of a coffee LCA will be very different if the objective is to analyse one farm, a national average or a roaster supply area for instance. As mentioned earlier, LCI data need to be adapted to the goal and scope, meaning representative of the actual studied system in all its dimensions (geographical, temporal and technical). Given the great variability in coffee farming and first processing systems (*c.f.* section 2.1), defining the sampling approach may be critical to reach the study goal.

Across the guidelines, there are three sampling options:

1. Complete sampling: could be considered when calculating a carbon footprint from individual plantations or for the assessment of processing and storage facilities;
2. Random sampling: relevant when calculating the carbon footprint of a coffee cooperative in which the farms and practices are homogeneous (CFP-PCR).
3. PAS2050:2012 offers an alternative of random sampling that could be applied even if farms are not homogenous: The minimum sample size can be determined via a statistical

approach that is further explained in the "Guidelines for the Carbon Footprinting of Dairy Products in the UK, 2010" (Chapter 4 and Appendix 3). More details on its application within a broader decision context is provided in the recommendations (*c.f.* section 3.1).

4. Stratified sampling: first identify representative clusters (*i.e.* sub-groups) within the complete population of farms. Clusters should be chosen based on characteristics that have a significant influence on the results such as management type (organic vs. other), shade type, climate. In other words, clusters gather growers that are expected to have a similar Carbon footprint. Clustering reduces the standard deviation within each group, thus reducing the number of farms that must be sampled to reach an acceptable margin of error.

In this case, the CFP-PCR and PAS 2050:2012 recommend *a sample size equal to the square root of the full population size.* The sample size in each cluster should reflect the proportion of product supplied (then a weighted average can be calculated).

Note: the sampling effort should be based on the proportion of the product supplied by each sub-group (not the number of suppliers for each group); thus, the average dataset will be weighted according to the percentage supplied.

The reporting must clearly state the approach applied, the sample size and how this was established.

The time dimension is one of the most complex dimensions to apprehend in LCA, which is time-disconnected by nature due to the integrated snapshot (except for dynamics LCA). In agricultural LCA, time is critical due to the impact of climate and varying practices from year to year. Furthermore, in the case of perennial cropping systems, the time dimension is even more complex to integrate due to varying practices and delayed impacts along the crop cycle (Cerutti et al., 2011; Bessou et al., 2013). In any case, the sampling strategy must also consider this time factor.

In the CFP-PCR, they recommend that the most recent three consecutive years be averaged, without further details (Figure 8). The PAS2050:2012 is more specific for perennials: the three-year period should correspond to a "steady state" situation. If not, GHG emissions shall be corrected by bringing the areas of different growing stages in proportion to the expected proportion in steady state. Finally, the PCR for Moka and Espresso (2019) mentions that unproductive years of the coffee plantation shall be considered (not the CFP-PCR for green coffee). The consumptions and emissions of unproductive years of the coffee plantation shall be spread out over the productive years considering the yearly yields and entire lifetime of the plantation. Guidelines are hence not consistent regarding that matter, so that we shall made more specific recommendations (*c.f.* Section3.2).

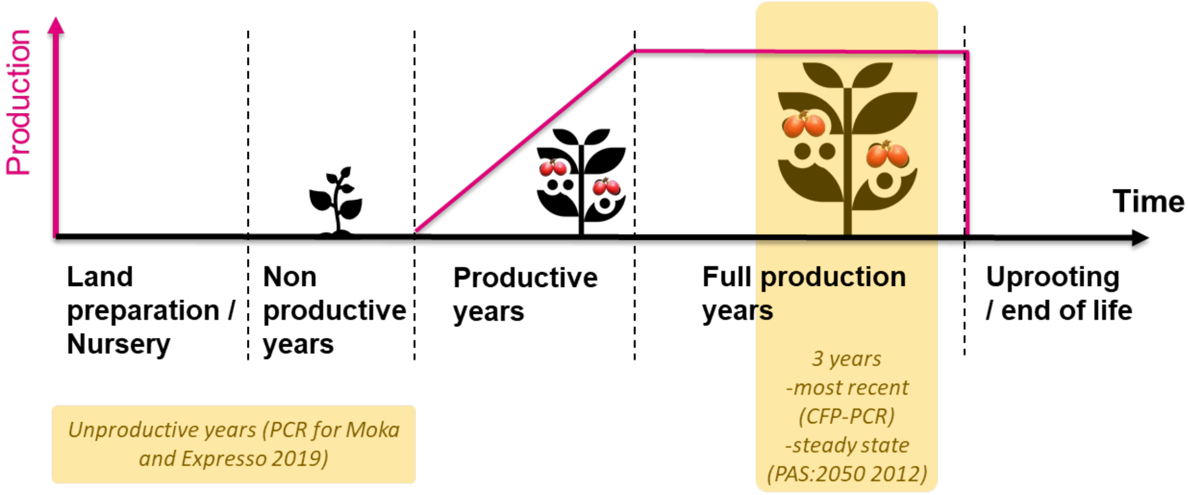

Figure 8. Representation of the various stages of a coffee plantation that should be accounted for (in yellow) according to the guidelines.

Allocation

When co-products remain in the system (*e.g.* husks used as fertiliser or energy used in bio-digesters in the mill), no allocation is necessary (CFP-PCR).

The guiding principles for allocation in the CFP-PCR are aligned with the allocation procedure described by ISO 14044 and ISO 14067:

1. Allocation should be avoided by dividing the unit process into 2 or more sub-processes, or by expanding the product system to include the additional functions related to the co-products.
2. Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions that reflect the underlying physical relationships.
3. Where physical relationships cannot be established or used, the inputs should be allocated between products and functions in a manner that reflects other relationships between them.

All guidelines propose to avoid allocation as first choice, but still provide recommendations on allocation since it may be sometimes unavoidable. So, the general principles are further specified in the CFP-PCR, with two types of allocation:

A. Allocation of input quantities and processes between the different crops in polycultures and

B. Allocation of GHG emissions from multi-output systems

A. Allocation rule hierarchy of input quantities between the different crops in polycultures:

- Fertiliser inputs and irrigation:
    1. Break down the process into sub-processes by obtaining primary data on fertiliser use for each crop. Manure 'production' is allocated 100% to the animal with transport, storage and on-farm handling all to be allocated to the coffee production.
    2. If collecting data on the quantities of fertilisers for all crops is not possible, the farmers should be encouraged to estimate the data for coffee.
    3. If this cannot be done, use the default value tables (based on an agronomic approach using the N requirements of the different plants – *c.f.* Table 3). If practitioners have other higher

quality or more representative data, they should be used preferably. The CFP-PCR specifies future updates may include other crops and cater for situations where there is more than one other crop.

4. If this cannot be done, use economic allocation
5. If there are more than one crop or if the crop is not in the table: allocate 100% to coffee.

Table 3. Recommended default values of nitrogen uptake as allocation parameters for Arabica and Robusta coffee in intercropping systems (Adapted from CFP- CPR Green Coffee)

Intercropping system	***Arabica Coffee (kg N / kg coffee cherry)***	***Robusta Coffee (kg N / kg coffee cherry)***	***Other crop (kg N / kg crop)***
Coffee - Avocado	0.023+0.006	0.012+0.005	0.003
Coffee - Banana	0.023+0.006	0.012+0.005	0.006
Coffee - Bean (green)	0.023+0.006	0.012+0.005	0.008
Coffee - Citrus	0.023+0.006	0.012+0.005	0.002
Coffee - Durian	0.023+0.006	0.012+0.005	0.001
Coffee - Maize	0.023+0.006	0.012+0.005	0.024
Coffee - Mango	0.023+0.006	0.012+0.005	0.007
Coffee - Papaya	0.023+0.006	0.012+0.005	0.002
Coffee - Pepper	0.023+0.006	0.012+0.005	0.018
Coffee - Plantain	0.023+0.006	0.012+0.005	0.006

- Fuel use:

If crop specific data are not available, use economic allocation based on local values averaged over a 3-year period.

- Pesticides and herbicides inputs:

No allocation unless the product has an impact on both coffee and co-crop. If pesticide/herbicide are applied to the ’benefit of both species, the allocation approach for fertiliser should be applied.

B. Allocation of GHG emissions from multi-output systems:

In case of allocation between coproducts that are exported out of the system, an economic approach is to be applied using local values averaged over the previous three-year period. Below more specifications from the CFP-CPR:

- Exported husks:
    1. Economic approach based on local value,
    2. Proxy based on local price of fertiliser ‘N’ and equivalent ‘N’ in the husk.
- Timber sold on off farm (from pruning or replacement processes):
- Economic approach where values have been averaged over the previous three years

- Gas or electricity exported from the mill:

Economic approach using local grid price.

- Husks sold for energy generation:

    1. Economic (three-year average value) approach,
    2. Proxy based on alternative fuel sources and comparative calorific value for the husks generated

The allocation of pesticides or herbicides inputs is debatable: when a pesticide/herbicide is applied to the ’benefit of both species’ (this is often the case), the allocation approach specified above for fertiliser is to be applied: 1. Breaking down is not relevant in this case, 2. The default table based on N requirement is not relevant, 3. Economic allocation may be the best option.

Recycling of co-products and GHG emissions

The CFP-PCR requires:

- Where there is recycling activity (ex: husk used for fertiliser), this will be included in the calculation; where appropriate the benefits will be recognised through the calculation displacing fossil sources that would have otherwise been used.
- If there is an inflow of recycled material to the system in the production/processing phase, the recycling process and the transportation from the recycling process to where the material is used shall be included.
- If there is an outflow of material to recycling, the transportation of the material to the recycling process shall be included. The material going to recycling is then an outflow from the production system.

2.2.2 Life Cycle Inventory

Emissions

According to CFP-PCR, emissions to be included are as follow:

- Fossil carbon dioxide (energy use, *e.g.* combustion of diesel and some forms of electricity production)
- Fossil methane emissions
- Biogenic methane emissions (wet processing water treatment)
- Nitrous oxide emissions (N_2O emissions from fertiliser production and application of both mineral and organic fertilisers as well as ‘N’ contained in pruning residues returned to the soil through cultivation)
- Carbon stock changes due to land use change (LUC) within the last 20 years in order to establish the coffee plantation (Following the guidance provided by the Greenhouse Gas Protocol – Product Life Cycle Accounting and Reporting Standard, Appendix B, Page 119, applying scenario B). Can be reported separately, but must be reported.

Emissions excluded:

- Emissions associated with the ‘short’ carbon cycle where photosynthesis and respiration are the primary components

- Emissions from biogenic sources (as per the PAS2050 (2011) guidelines, section 5 – Cf. “Short carbon cycle” and note below)
- Carbon sequestration in above and below-ground biomass (other than in the context of land use change) – but CFP-PCR actively encourages practitioners to report the sequestration figure separately to the core results.
- Soil carbon changes (other than in the context of land use change) which is not aligned with the ISO 14067

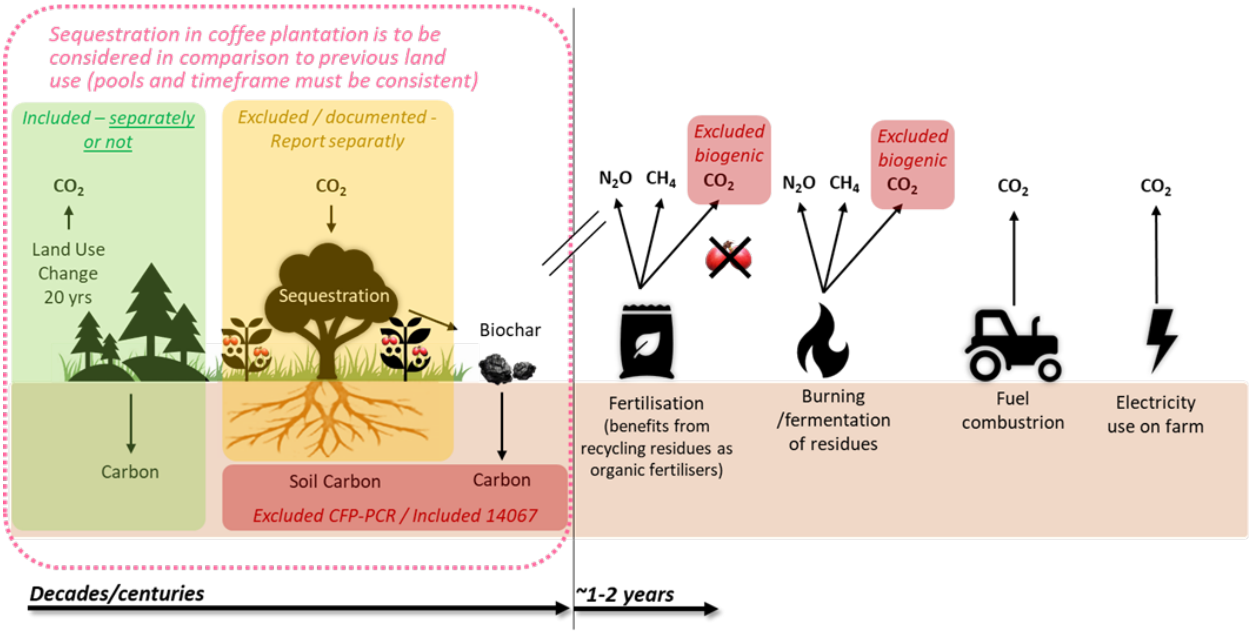

Figure 9. Summary of GHG emissions included or excluded in the Carbon Footprinting. Discrepancies between guidelines are highlighted.

“Short biogenic carbon cycle”

For food and feed, emissions and removals from biogenic sources that become part of the product are excluded because the carbon is not stored for a long period. They are considered neutral from a global warming point of view.

There are exceptions to this rule in PAS2050 and CFP-PCR for green coffee (*i.e.* biogenic carbon emissions and removal to include):

> emissions and removals of biogenic carbon used in the production of food and feed (*e.g.* in burning biomass for fuel) where that biogenic carbon does not become part of the product;

> non-CO_2 emissions arising from degradation of waste food and feed and enteric fermentation (given differences in radiative forcing of various C-compound GHG);

> any biogenic component in material that is part of the final product but is not intended to be ingested (*e.g.* packaging).

In addition to these exceptions, emissions and removals from biogenic sources within the frame of long-term LULUC should be accounted for (biogenic CO_2 is not considered as neutral in this context due to the long-term time frame).

Methodological gap/flexibility:

- Soil carbon shall be included according to ISO14067, but excluded in CFP – PCR Green Coffee (2013). Although carbon storage (both soils and standing biomass) holds a potentially significant mitigation opportunity for the coffee production sector, the CFP-PCR recommends to exclude changes in soil organic matter (carbon) and standing biomass, but encourages to report the sequestration figure separately. It is intended to fully incorporate carbon sequestration calculation guidelines once scientific developments and necessary data are generated.
- There is a confusion created by these different guidelines when distinguishing carbon stock changes due to LUC or not. Carbon sequestration on a given land area in any pool, including soil organic carbon, actually depends on the previous land use change, because carbon catch and release by the biosphere is a time-dependent process so that no proper sequestration can actually be considered if the time frame is too short. While all the guidelines refer to some part of IPCC guidelines (2006), the only way to be consistent is to consistently apply IPCC Tier 1 for both LU and LUC stock variations (*c.f.* section 3.3). IPCC Gain-Loss method proposes a more dynamic approach to stock changes that may rely on shorter time frames but those are only consistent at national levels, where different areas may be at complementary development stages. Those are hardly relevant for product chains.

Sequestration in any coffee plantation is to be considered in comparison to previous land use (pools and time frame must be consistent). Given the critical impact of LULUC on carbon footprint, we dedicated a complete section of recommendations to this matter.

Data origin

The CFP-PCR emphasises the collection and use of ‘specific’ data (gathered from the actual activity or outcome where product-specific processes are carried out) that we also referred to as site-specific data in the report (*c.f.* glossary). Specific data are required for the farming and milling operations. The environmental impact of the processes where the other generic data are used must not exceed 10% of the overall environmental impact from the product system.

It is important to mention that the terminology regarding the type of data varies among guidelines. While CFP-PCR focuses on site-specific data, ISO 14067 differentiates between site-specific data and primary data as follows: All site-specific data are primary data but not all primary data are site-specific data. Indeed, the ISO 14067 specifies that *“Primary data that are not site-specific data, based on global or regional averages, collected by regional or international organisations and which have undergone third-party verification should be used when the collection of site-specific data is not practicable”*. Varying terminologies create confusion, so that carbon footprint studies should always display a glossary of key terms.

Data quality

Data should be of quality that reduces uncertainty and bias as much as possible. ISO 14067 and GHG protocol provides criteria regarding data quality, but, as mentioned in the CPF-PCR, the most extensive recommendations can be found in the ILCD handbook (now PEF).

According to ISO 14067, data quality shall be characterised by both quantitative and qualitative aspects and characterisation should address the following:

a) time-related coverage: age of data and the minimum length of time over which data should be collected;
b) geographical coverage: area from which data for unit processes should be collected;
c) technology coverage: specific technology or technology mix;
d) precision: measure of the variability of each data value expressed (*e.g.* variance);
e) completeness: percentage of flow that is measured or estimated;
f) representativeness: qualitative assessment of the degree to which the dataset reflects the true population of interest (*i.e.* geographical, time period and technology coverage);
g) consistency: qualitative assessment of whether or not the study methodology is applied uniformly to the various components of the sensitivity analysis;
h) reproducibility: qualitative assessment of the extent to which information about the methodology and data would allow an independent practitioner to reproduce the results;
i) sources of the data;
j) uncertainty of the information (*e.g.* parameter uncertainty for EFs and activity data)

Note that some of the above-mentioned criteria are redundant. For a more practical data quality assessment, the ILCD / PEF guidelines are providing an interesting approach we summarised in section 3.1.2.

The ISO 14067 mentions that “specific values for data quality requirements can be specified in a CFP-PCR”. Thus, this could be improved in the next update of the CFP-PCR.

Emissions factors

Emission factors provide an indication of the quantity of GHGs emitted from a particular source or activity. GHG emissions shall be calculated using the IPCC Guidelines for National Greenhouse Gas Inventories. Although the CFP-PCR encourages “Tier 2” or “Tier 3” approach (respectively based on country-specific information or individual data), the simplest approach “Tier 1” is considered appropriate.

It is important to note that various sources need to be combined in order to get the most updated values for the various emission factors. Table 9 and Table 10 in section 3 provides more details on default emissions factors and databases.

2.2.3 Life Cycle Impact Assessment

As shown in Table 4, Global Warming Potentials (GWP) relative to CO_2 for the 100-year time horizon for the various GHG are varying depending on the IPCC Assessment Report years. The GWP actually used in calculations should be the latest available from the IPCC (PAS2050:2011 and ISO 14067). “latest” version is not mentioned in the PCF-PCR.

We recommend checking IPCC updates on GWP and clearly reporting which version was used in the applied LCIA method. One should be also aware that some LCIA methods may use various versions of those IPCC GWP. RECIPE (2016), for instance, is based on 20-year, 50-year or 100-year integrated GWP depending on the societal model selected. The hierarchist model RECIPE (H) is the most commonly used and relies on the 100-year integrated GWP.

Table 4. Global Warming Potentials (GWP) for Carbon dioxide (CO_2), Fossil and Biogenic Methane (CH_4) and Nitrous oxide (N_2O) provided by the International Panel on Climate Change (IPCC) in 2007 and 2021.

GHG	***IPCC 2007*** ***GWP 100-year time period*** ***Feedbacks not included*** ***[kg CO_{2e}/kg]***	***IPCC 2021*** ***GWP 100-year time period*** ***Feedbacks included*** ***[kg CO_{2e}/kg]***
CO_2	1	1
Fossil CH_4	25	29.8
Biogenic CH_4		27.2
N_2O	298	273

2.2.4 Interpretation, reporting & communication

Interpretation

The PCF-PCR does not provide any information on interpretation. We thus referred to the ISO 14067 guidelines providing the required steps:

1. Identification of the significant issues based on the results of the quantification of the CFP according to LCI and LCIA phases;
2. An evaluation that considers completeness, sensitivity and consistency checks;
3. Conclusions, limitations, and recommendations.

Results shall be interpreted according to the goal and scope of the study and shall:

- Include a quantitative and/or qualitative assessment of uncertainty,
- Identify and document the selected allocation methods (section 2.2.1.),
- Identify the limitations of the study, including:
  - The focus on climate change as the single impact category: decisions about product impacts that are only based on a single environmental issue can be in conflict with goals and objectives related to other environmental issues)
  - Limitations related to the methodology (*e.g.* system boundary, availability and selection of appropriate data sources, allocation rules, assumptions regarding the transport)
  - Ideally, interpretation should also include:
- a sensitivity check for significant inputs, outputs and methodological choices (including

allocation methods) in order to understand the sensitivity and uncertainty of the results

- an assessment of the influence of alternative use profiles and end-of-life scenarios on the results.

Study report

Contrary to the PCR for Espresso and Moka, the PCF-PCR for green coffee does not provide details regarding the report structure and requirements apart from mentioning the principles of the WRI's Greenhouse Gas Protocol Product Life Cycle Standard[19] (Relevance, Completeness, Consistency, Transparency and Accuracy) and referring to the ISO 14067. Next update of the PCR-PCR for green coffee should be more specific on this aspect.

Communication

Requirement for reporting/communication depends on the goal and scope of the study. A key purpose of CFP communication is for users of the product to make informed choices. CFP communication may have different objectives and take various forms. Details on the report content for each CFP option are provided in ISO 14067. General requirements and guidelines for the four CFP communication options are addressed in the ISO 14067 and are summarised in Figure 10.

CFP form / objective:	**CFP external communication report** based on the CFP study report, intended to be communicated externally	**CFP performance tracking report** comparing the CFP of one specific product of the same organization over time	**CFP Label** mark on a product identifying its CFP within a particular product category according to the requirements of a CFP communication programme	**CFP Declaration** declaration of the CFP made according to the CFP-PCR or relevant PCR
Publicly available?	Yes / No	Yes / No	Yes	Yes / No (same requirements)
CFP communication:	optional	optional	mandatory	mandatory
CFP-PCR:	optional	optional	mandatory	mandatory
3rd party CFP verification or disclosure report:	mandatory (optional if not intended to be publicly available)	mandatory (optional if not intended to be publicly available)	mandatory	mandatory

Figure 10. General requirements and guidelines for the different CFP communication options intended to be publicly available or not. Note: "publicly available" means a communication which is deliberately placed in the public domain or intended to be available to consumers. (adapted from ISO 14067:2006)

CFP external communication report and performance tracking report are primarily intended for business to business communication. Conversely, CFP label and declaration are usually intended for consumer communication (although CFP declaration may not be publicly available).

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[19] https://files.wri.org/d8/s3fs-public/pdf/ghgp_product_life_cycle_standard.pdf

When an organisation decides to make a CFP communication publicly available, regardless of the chosen CFP communication option, CFP communication shall either:

a) be verified by a third party in accordance with ISO 14025, based on CFP quantification that has undergone an external critical review according to ISO 14044, or
b) be supported by a CFP disclosure report.

The external critical review and third-party CFP verification of the CFP communication can be undertaken at the same time (ISO 14067). The verification is a confirmation, through provision of evidence, that specified requirements related to a CFP study and a CFP communication have been fulfilled (verification originates from the ISO 14025 standard establishing the principles and procedures for developing Type III environmental declarations and programmes). Whereas the critical review intends to ensure consistency between the CFP study and the principles and requirements according to the principles, methodology for CFP quantification and reporting defined in the ISO 14067 (critical review originated from the ISO 14044).

For CFP label and CFP declaration, there are two additional requirements:

- relevant CFP-PCR
- CFP communication programme (*i.e.* programme for the development and use of CFP communication based on a set of operating rules. It may be voluntary or mandatory, international, national or sub-national).

The PCF-PCR for green coffee does not provide detailed information on the verification requirements whereas the PCR for espresso and Moka coffee specifies that the EPD report shall be verified by an approved individual or accredited certification body. EPDs are then registered and published online, and are valid for five years.

2.2.5 Guideline comparison summary table

Table 5. Summary table – Carbon footprint guideline comparison

Standard/ guideline	***ISO 14067 (2006)***	***PAS 2050:2011 and PAS 2050:2012***	***CFP-PCR Green coffee (2013)***
Description	Adaptation of ISO 14040/44 to specific climate change issues	Developed by the British Standards Institution. Aims at providing a consistent internationally applicable method for quantifying product carbon footprints	Developed under the International EPD® System, building on resources and selecting the most appropriate approach to best suit green coffee
Allocation or co-product handling	1. Avoid by subdivision 2. Avoid by system expansion 3. Use physical relationships 4. Use other relationships (e.g economic)	1. Avoid by subdivision or system expansion 2. Input to multiple crop: allocation based on crop needs 3. Mass allocation if co-products have same properties/function 4. Economic allocation if co-products have different properties/function	1. Avoid 2. Use physical relationships 3. Use other relationships Specific recommendations: - allocation of fertiliser, irrigation, pesticide and fuel inputs,

Standard/ guideline	***ISO 14067 (2006)***	***PAS 2050:2011 and PAS 2050:2012***	***CFP-PCR Green coffee (2013)***
			- allocation of emissions for exported co-products (timber, husks…)
Functional Unit	shall be that defined in the CFP-PCR	Quantity – Function - Properties	1 kg of Green Coffee at 11.5% moisture delivered to […]
System boundary	cradle-to-grave or cradle-to-gate	cradle-to-grave or cradle-to-gate	cradle to the 'port of origin' or cradle to the warehouse of the domestic roasting facility
Cut off	the effect of the selected cut-off criteria shall be assessed	at least 95% of the anticipated life cycle GHG emissions and removals associated with the functional unit.	at least 95% of climate change potential associated with the declared unit shall be included
Data collection time period - Perennial	not available	three year rolling average in a 'steady state' situation (or by bringing areas of different growing stages in proportion to the expected proportion in steady state)	the most recent three consecutive years averaged
Emissions from biogenic sources	included and reported separately. Zero net emissions if CO2 taken up in biomass not converted into methane or NMVOC	excluded apart from not part of the product/not ingested/from degradation of waste food	excluded apart from biogenic methane from fermentation of residues
Carbon stock changes due to LUC within the last 20 years	*LUC GHG emissions & removals shall be documented separately* (using IPCC which includes the 20-year time frame as default).	included (LUC occurring not more than 20 years or a single harvest period)	included (can be reported separately)
Carbon sequestration in above & below-ground biomass (w/o LUC) should be also within 20 yrs	shall be documented separately (not detailed)	carbon stored beyond the assessment period is treated as stored carbon	excluded but encouraged to report separately
Soil carbon change from land management (w/o LUC) should be also within 20 yrs	included using IPCC guidelines	excluded (unless provided for in supplementary requirements)	excluded
GWP	Latest GWP 100 from IPCC	Latest GWP 100 from IPCC	GWP100 from IPCC 2007 – no recommendation for using the latest version

2.3 Review to fill specific gaps

Main identified gaps concerned the quantification of biomass and related LUC impacts, the identification and accounting for co-products, waste and their emissions, and the use of biochar. A review of the knowledge available was carried out in order to provide recommendations on methods and data to be used.

2.3.1 Biomass estimation and allometric data

Biogenic carbon is stored in the above- and belowground biomass of the coffee plantation (coffee bushes and other trees) among other carbon pools. Biometric measurements of bushes or trees are converted into biomass values using empirical allometric models. An allometric model is a mathematical equation that allows relating one or more easily measured variables (for example diameter at 15 cm for coffee bushes or diameter at breast height for shade trees, height, age) to estimate a variable otherwise difficult to measure (for example volume, biomass, carbon). Such allometric equations are therefore commonly used to assess the above- and belowground biomass. In this section we reviewed the existing estimations and ways to assess these two pools of carbon.

2.3.1.1 Arabica coffee

Field measurements of above-ground and below-ground biomass in Arabica coffee trees have yielded several allometric models, fitted with either the measured stem diameter, coffee tree height, or a combination of both. Stem diameters are often measured at 15 cm or 40 cm from the ground for maximum accuracy (Segura 2006, Andrade 2018, Negash 2013). However, in the case of regularly stumped coffee trees, large stumps prevent these measurements close to the ground, in which case the diameters are measured on top of the stump and at the base of new re-sprouting stems, or at breast height (Lugo-Pérez 2023). The stump biomass can then be estimated separately from the other tree components (Segura 2006, Defrenet 2016). When coffee trees are managed with several stems, some authors tend to favour the use of basal area to aggregate the multiple stems of one coffee plant before fitting their allometric model (Defrenet 2016, Lugo-Pérez 2023). We only found one allometric model fitted on stem circumferences (Guillemot 2018). All allometric models expressed the biomass in mass of dry matter (DM) (Figure 11).

The various allometric models show that the above-ground biomass of coffee trees with a stem diameter between 4 cm and 8 cm ranges from 1.5 to 5 kg DM/tree in the case of dwarf coffee cultivars planted at high densities (2500-6000 tree/ha). Negash (2016) suggests the only allometric model with significantly higher estimates of above-ground biomass, up to 78 kg DM/tree for trees with stem diameters of 23 cm. However, this model applies to old Ethiopian varieties, with much larger (5-23 cm) and higher (5-7 m) stems than the usual dwarf coffee cultivars, as well as much lower planting densities. Only in these specific conditions can this model apply.

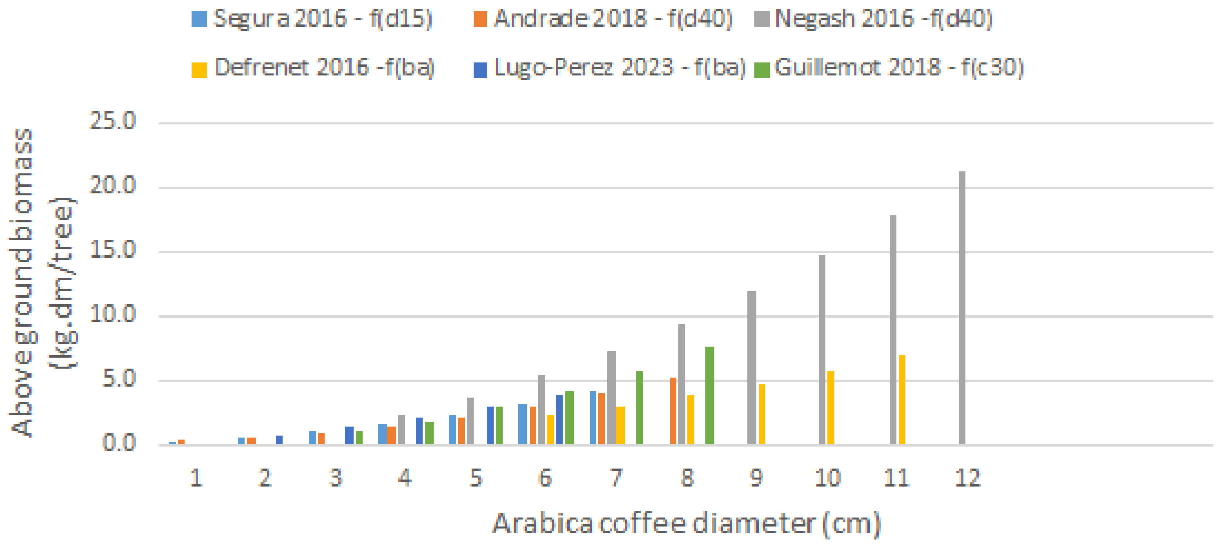

Figure 11. Above-ground biomass of arabica coffee trees estimated from several allometric models within their range of application. Allometric models were fitted with stem diameter at 15 cm (d15), stem diameter at 40 cm (d40), basal area (ba), or stem circumference at 30 cm (c30)

Note 1. we assume 2 stems per coffee trees in Defrenet (2016) and Lugo-Perez (2023)

*Note 2: d15 is approximated as DBH*2 in Lugo-Perez (2023)*

Note 3: values from Defrenet (2016) only consider the biomass from the stump itself, not considering the biomass from the stems, therefore underestimating the total above-ground biomass

Note 4: projected crown area is estimated at 4 m^2/tree in Guillemot (2018)

Note 5: Basal area and stem circumferences were converted into stem diameters when needed, using simple geometry.

When using allometric models, it is crucial to keep in mind orders of magnitude to check and validate the results. The above allometric models all yield similar orders of magnitude of above-ground arabica coffee biomass per tree or per unit area. The following section details rough calculations to help readers grasp these orders of magnitudes[20].

Considering arabica coffee farm densities around 5,000 trees/ha in the case of intensively managed dwarf cultivars, as is common in Latin America, and an average AGB around 1.5 kg DM/tree (Segura 2006, Andrade 2018), the AGB per unit area amounts to 7.5 t DM/ha. In case of older trees, the AGB can fetch up to 4 kg DM/tree, and the AGB per unit area can go up to 20 t DM/ha. Teran-Ramirez (2018) finds a similar result in Mexico, with 5 t DM/ha in coffee systems under low levels of shade and less intensive management practices. The AGB can go as low as 1 t DM/ha in highly shaded and diversified systems. These rough orders of magnitude still hold in very different systems. For example, in shaded coffee systems based on larger coffee trees planted at the lower density of 2,200 trees/ha in India, Guillemot (2018) observes AGB between 0 and 5 kg DM/tree, and an average AGB per unit area between 6 and 10 t DM/ha. Going one step further in completely different coffee systems, in the case of old coffee trees in forest-gardens in Ethiopia (Negash 2013), the average above-ground biomass goes up to 23 kg DM/tree. However, with an estimate density of 400 to 500 coffee trees/ha commonly found in these traditional enset-coffee gardens (Abebe et al., 2013), the AGB would amount to 10 t DM/ha, once again within the same order of magnitude as the other coffee-agroforestry systems.

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[20] Defrenet (2016), Ehrenbergerova (2016) and Niguse (2022) were discarded from the calculations of orders of magnitude, for there were concerns regarding either their datasets or some other important indicators in these articles

2.3.1.2 Robusta coffee

There is less information available for Robusta coffee growth than for Arabica coffee growth. The only peer-reviewed allometric equation found to estimate above-ground biomass of *Coffea canephora* was modelled after coffee trees found in Indian agroforestry systems (Guillemot 2018). This equation relies on the stem circumference at 30 cm as well as the projected crown area. Another study, conducted in Cuba, shows a growth curve for the first five years of Robusta coffee trees after planting or after pruning, and constitutes an interesting comparison (Bustamante 2015) (Figure 12. *Comparison of above-ground biomass for Robusta coffee trees planted at a density of 2 222/ha*

For the purpose of comparison, we made the rough assumption that the stem diameter at 30 cm increases by 1.0 cm/year (Podong (2021) estimates the DBH growth at 0.7 cm/year). Furthermore, the projected crown area is estimated from the planting density (for instance a density of 2 222 trees/ha in Bustamante (2015) results in PCA = 4.5 m^2). Under these assumptions, the above-ground biomass estimated from Bustamante (2015) is higher than the above-ground biomass estimated from Guillemot (2018)'s allometric equation, but the gap between the two curves is narrowing down towards 4 to 5 years old. Considering that Guillemot (2018) developed its allometric model from older coffee trees, it makes sense to avoid its use for coffee trees below 5 years old and to rely on it for older coffee.

In Cuba, the Robusta coffee trees are pruned after 5 years, when the above-ground biomass reaches 16.5 t DM/ha. This coincides with the fact that the biomass accumulation curve is slowing down, and it therefore could be expected that the biomass accumulation would reach a plateau after a few more years without rejuvenation, roughly around ~10 kg DM/tree, equivalent to ~22 t DM/ha under their planting density of 2 222 trees/ha. In comparison, in Vietnam, coffee trees are planted at a theoretical density of 1111 trees/ha but an average density of 1,000 trees/ha (Rigal 2023). Guillemot (2018) indicates that 10 to 15-year old trees would sequester an average 14-24 kg DM/tree, thus an approximate 14-24 t DM/ha, in line with the estimated 20 t DM/ha from D'haeze (2021)[21] (also relying on Guillemot 2018) and with the 34-38.7 t CO2eq/ha equivalent to 18.5-21 t DM/ha from Kuit (2020).

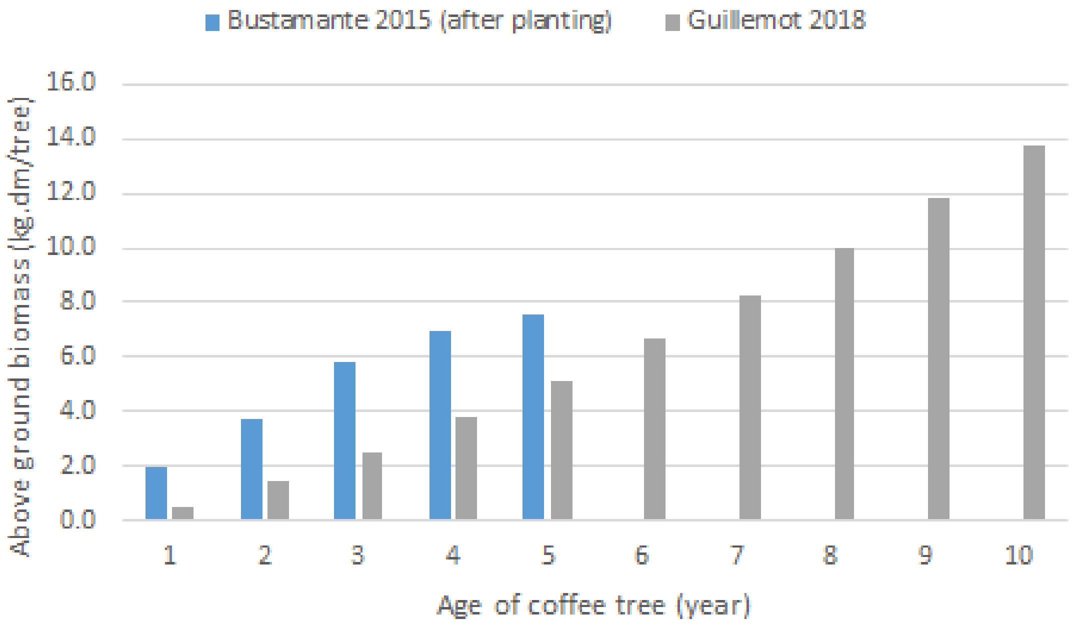

Figure 12. Comparison of above-ground biomass for Robusta coffee trees planted at a density of 2 222/ha

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[21] From D'haeze 2021 report Optimizing water use in the Central Highlands of Viet Nam

It should be noted that an allometric model based on tree age was developed by Kuit (2020) for Robusta coffee in Vietnam. However, this specific growth curve yields unreasonable results: for instance, the above-ground biomass of 3-year old coffee trees would amount to 30 kg DM/tree, more than 5 times the values of Bustamante (2015). We believe that this may come from a mistake in units or in one of the formulas displayed in the report. Indeed, other results from that same report are in line with Guillemot (2018). In particular, it is said that monocropping coffee systems store 40 t C/ha, equivalent to 24 kg DM/tree for a density of 1,008 trees/ha and coffee trees on average 15 years old (D'haeze 2021, Kuit 2020). With the above assumptions, Guillemot (2018) also estimates the above ground biomass of 15-year old coffee trees at 24 kg DM/tree.

2.3.1.3 Shade trees

In agroforestry systems, most of the above-ground biomass belongs to shade trees. The precise estimation of standing biomass in shade trees is thus more impactful to the total carbon balance than the precise estimation of biomass in coffee trees. Yet, the high diversity of intercropped tree species and the large range of growing conditions increase the complexity of analysis. In the section below, we divide shade tree species into two categories: fruit trees vs other trees.

Fruit tree species

When it comes to fruit trees, there are a number of published articles estimating their standing biomass. However, a close look at their methodology reveals that the majority of these studies rely on a single allometric model, sometimes referred to Andrade et al. (2008), and other times referred to as Somarriba et al. (2013). Both references actually provide the same allometric model, based on an unpublished dataset derived from CATIE institute.

AGB of fruit tree (kg DM/tree) = 0.0776 * DBH (cm) ^ 2.64 Equation 1

Range of application: DBH from 1.9 to 46.5 cm

Interestingly, Kuit (2021) provides a database of species-specific allometric models for a panel of tree species commonly found in Vietnam, including jackfruit, durian, and avocado trees. However, these growth models are site specific since they are based on tree age rather than on shape-related input variables. In Northwest Vietnam, under less favourable growing conditions, it is estimated that jackfruit trees grow 2 to 3 times slower (Figure 13. C*omparison of the standing biomass in jackfruit trees based on 3 datasets: Kuit (2021) from Central Vietnam; an unpublished dataset from SIPA project for Northwest Vietnam; an unpublished dataset from Northwest Vietnam relating jackfruit age and DBH fed to the default allometric equation developed by Andrade (2008)*This shows the difficulty to generalise results from site-specific models. We actually suspect that Kuit developed a model of stem diameter as a function of tree age, and thereon used this data to model the aboveground tree biomass based on default allometric models, such as Andrade (2008), rather than felling trees and weighting their components. This strategy can provide relatively accurate and site-specific data at low cost.

Generally speaking, we discourage the use of allometric models based on age as the main input variable (example: Quantis report for Cool Farm Tool). These models are extremely simple to use, since they do not require on-farm measurement of tree size. They are also well adapted to the modelling of biogenic carbon sequestration throughout the whole duration of the farming system, as it is easy to change the age to estimate biomass at different times. However, they come with high levels of uncertainties related to tree growth rate, depending among others on local climate, soil, and management practices.

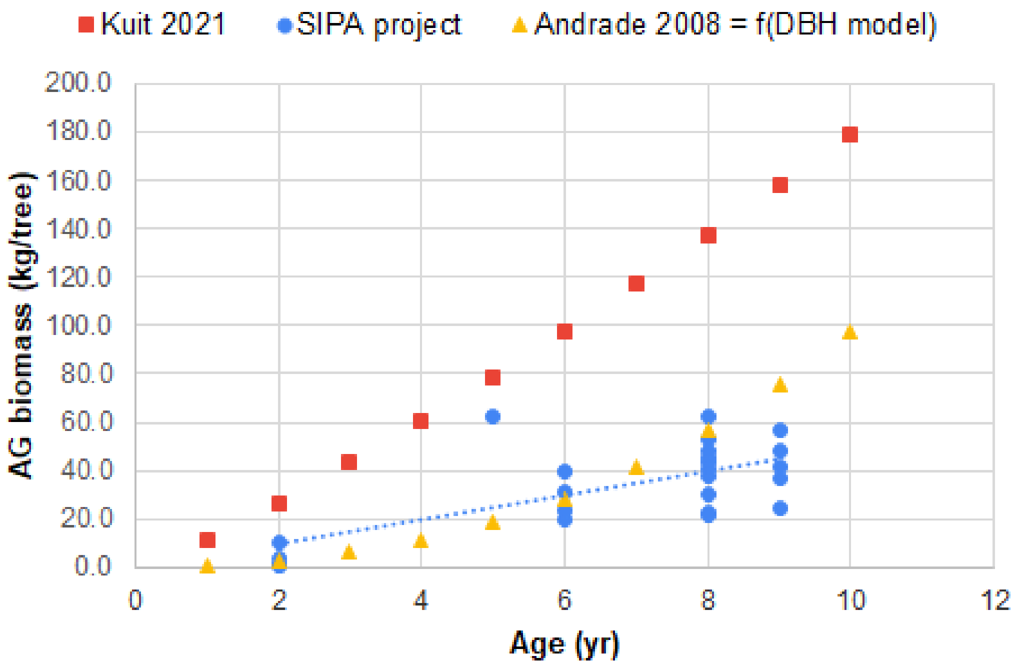

Figure 13. Comparison of the standing biomass in jackfruit trees based on 3 datasets: Kuit (2021) from Central Vietnam; an unpublished dataset from SIPA project for Northwest Vietnam; an unpublished dataset from Northwest Vietnam relating jackfruit age and DBH fed to the default allometric equation developed by Andrade (2008)

Other tree species

Many more allometric models are available for other tree species, from general models to species- and site-specific ones. Below are some examples (AGB is expressed in kg DM/tree, DBH in cm, Height in m) Figure 14:

- Chave (2014) for tropical forest stands:
  - Mixed species: AGB = 0.0673 * (q * DBH ^2 * H) ^ 0.976 Equation 2

where q is the wood density (g.cm-3)

- Acosta Mireles (2002) in Mexico:
  - Quercus, Liquidambar, Inga: AGB = 0.112 * DBH ^ 2.412 Equation 3
  - Alnus, Clethra, Rapaeca: AGB = 0.140 * DBH ^ 2.189 Equation 4
- Segura 2006 in Nicaragua:
  - *Inga* spp: AGB= 0.129 * DBH ^ 2.317 Equation 5
  - *Cordia alliodora*: AGB = 0.176 * DBH ^ 2.072 Equation 6
- Navar (2009) in tropical dry forests in Mexico:
  - Pinus spp: AGB = 0.123 * DBH ^ 2.396 Equation 7

- Quercus spp: AGB = 0.089 * DBH ^2.523 Equation 8

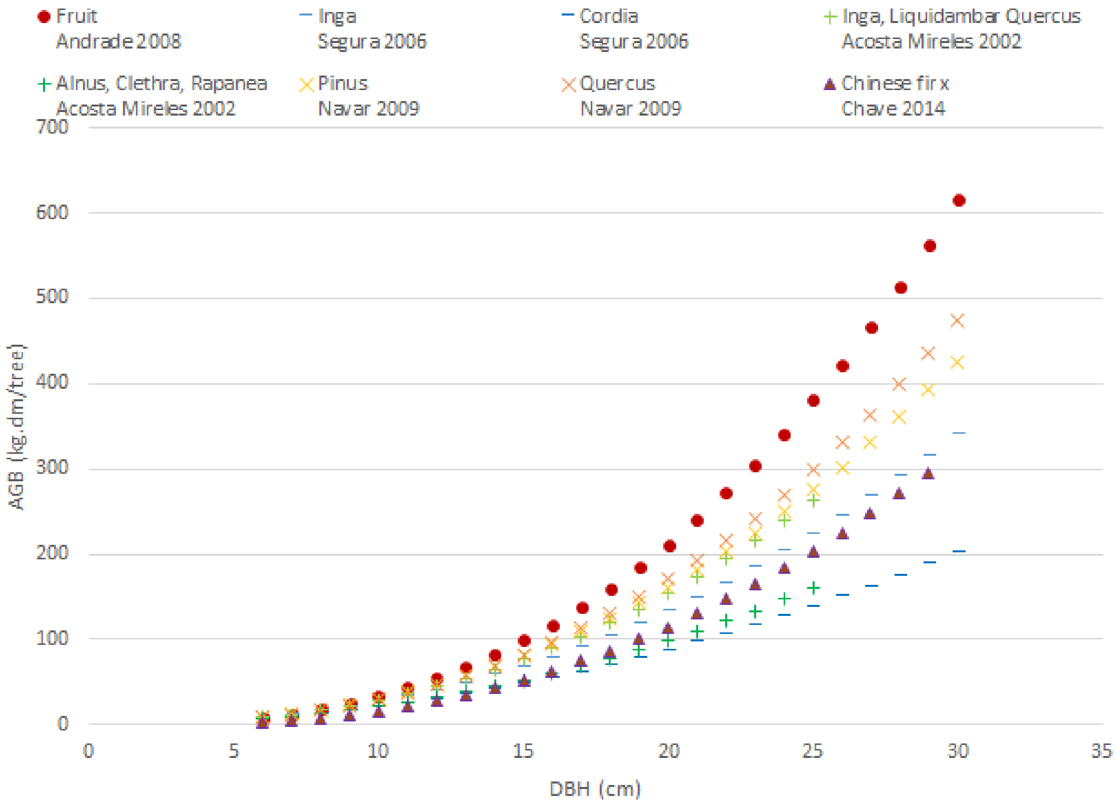

Figure 14. Comparison of several above-ground biomass allometric equations based on DBH. For Chinese fir, a relationship between DBH and H was derived from Li et al (2015) and fed into Chave (2014)'s allometric equation, considering a wood density of 0.3 g/cm^3

Surprisingly, the estimated above-ground biomass of fruit trees (Andrade, 2008) is always higher than that estimated for other trees. A possible reason to explain this difference might lie in the ratio of branch mass over stem mass (often referred to as biomass expansion factor) in fruit trees, higher than in most other tree species. Still, this raises the question of accuracy in Andrade (2008) allometric model. For this reason, and to avoid large overestimation in biomass for large fruit trees, we recommend to limit the use of Andrade (2008) to fruit trees with DBH ≤ 25 cm.

2.3.1.4 Below-ground biomass

Belowground biomass commonly accounts for approximately 20–30% of total carbon allocation of a tree (Armson, 1977; Young, 1989; Oelbermann et al., 2005) and can contribute to a considerable portion of the total inputs to soil organic matter (Nye and Greenland, 1962; Nye, 1960; Nair/Dury, 1989). For tropical and subtropical forests, the root to shoot ratio ranges in the IPCC 2006 guidelines (Annex 3A.1, Table 3A.1.8) between 0.24 and 0.42.

However, for coffee plantations, few studies exist concerning the assessment of belowground biomass. Dossa et al. (2008) quantified the total vegetation biomass and biomass distribution in a mature coffee plantation (*Coffea canephora var robusta*) with and without shade of *Albizia adianthifolia* in Southwestern Togo. Coffee coarse root biomass (>10 mm diameter) was estimated by excavating the coffee root from a 0.40 m deep hole stretching up to midpoint between the felled coffee bush and the next one. Biomass of fine roots (<10 mm diameter) was determined by means of a 20 x 20 x 20 cm^3 metal box with cutting edge used to take soil monoliths. For each coffee system, *i.e.* shaded coffee plot (1230 plants per hectare) and open-grown coffee plot (1267 plants per hectare), soil monoliths were taken from four random locations per subplot (replicate) at 0–20 and 20–40 cm depths. In this study, coarse roots of coffee bushes accounted for 3.6 +/- 0.4 t DM/ha and 10.7 +/- 1.1 t DM/ha for fine roots (from coffee bushes and Albizia trees) in shaded coffee plots. In open-grown coffee plots, coarse roots of coffee bushes accounted for 5.3 +/- 0.8 t DM/ha and 13 +/- 1.1 t DM/ha for fine roots. These values are slightly higher though similar to Guillemot et al. (2018). Therefore, Dossa et al (2008) assessed a belowground biomass to total stand biomass ratio of 0.19 in the shaded coffee system (coffee and shade tree combined), while 0.48 in the open-grown coffee system.

Defrenet et al. (2016) carried out a study in an agroforestry coffee (arabica) plantation (5,580 plants per hectare) in Costa Rica and measured the root biomass. They performed root excavation in the row and inter-row of the plantation to a depth of 150 cm, and extrapolated to the whole rooting profile (4 m) effectively colonised by roots, considering tap, coarse (<10 mm) and medium (2–10 mm) roots, as well as ephemeral (fine <2 mm) roots. They showed that the total root biomass in coffee plants was preferentially distributed just below the surface with nearly 30% of roots contained in the top 10 cm of soil and 55% in the top 30 cm of soil. This amount was 87% in the top 1 m and up to 92% at 1.5 m. Therefore, only 8% of the total root biomass was found at depth > 1.5 m. They found a value of 18.34 t DM/ha and a root to shoot ratio of 0.49 for all roots, or 0.29 for perennial roots only. This high ratio can be a consequence of the management practices, in particular the shoot pruning. The value of belowground biomass found in this study was comparable to the one found by Dossa et al. (2008). Indeed, considering that roughly 70% of the amount of root is found between 0 and 40 cm depth, for a shaded coffee system, approximately the belowground biomass would account for 20 t DM/ha according to data given by Dossa et al. (2008). Conversely, values of below ground biomass per coffee shrub are not consistent between the two studies likely due to very different planting density. Defrenet et al. (2016) developed the following allometric equation to assess the total root biomass:

$$Y = 14.96\ X + 1749.33 \qquad \text{Equation 9}$$

where Y is the total root biomass in gram of dry matter

and X is the basal area at collar in cm^2

This equation is valid for a diameter at the collar between 0 and 16 cm.

Another and last comparison point was found in Siles et al. (2010), which studied arabica coffee trees in Costa Rica, in both agroforestry and monoculture farming systems. The authors estimated the aerial biomass of coffee trees (excluding leaf) between 14.2 and 15.5 t DM/ha, and the below-ground biomass of coarse roots between 5.1 and 5.2 t DM/ha, therefore leading to a root-to-shoot ratio of 0.33-0.37. Furthermore, the sampling of fine root biomass (<2 mm) during the rainy season and at different locations related to the coffee row and inter-row, and to the distance to shade trees, resulted in an additional biomass of 4.1 to 4.7 t DM/ha.

The three above studies all agree that root-to-shoot ratios specifically developed for coffee trees are larger than root-to-shoot ratios developed for tropical forest. For coarse roots (> 2mm), a value of 0.40 seems reasonable for both Arabica and Robusta coffee trees. Such a default value does not consider fine roots that are repeatedly reported to compose a significant fraction of the below-ground biomass in coffee plantations. However, as highlighted in the IPCC Guidelines[22], it is often empirically challenging to distinguish fine roots from soil organic matter of litter. Similarly, Quantis justifies the exclusion of fine roots from carbon accounting since fine roots are assumed to die, decompose and regrow every year, while sequestering and emitting biogenic carbon dioxide, and modifying the soil organic carbon pool. Therefore, accounting only for coarse roots is simultaneously, more convenient, realistic and conservative.

It is also worth mentioning that several publications related to coffee plantations apply the allometric equation developed by Cairns et al. (1997):

$$\text{Root biomass (t DM/ha)} = \exp(-1.0850+0.9256*\ln(AGB)) \qquad \text{Equation 10}$$

According to this equation, the root to shoot ratio ranges between 0.23 and 0.34. However, this equation was developed for upland forests and is therefore not specific to coffee plantations. According to the above coffee-specific studies, it leads to underestimating the below-ground biomass of coffee. A higher value of root to shoot ratio should be applied for coffee plantation to fully consider the whole rooting depth and the large number of fine roots, especially in the case of regularly stumped coffee trees.

2.3.1.5 Biomass and carbon per area unit

The review of studies reporting values for both above and below-ground biomass was illustrated in Figure 15. The figure does not report all studies in an exhaustive manner; it aims at illustrating the balance between, on the one hand, biomass in coffee trees versus biomass in associated trees, and on the other hand, the balance between above-ground and below-ground biomass.

From this representation, it appears clearly that the biomass increases with the complexity of the farming systems: Full sun monoculture < simple agroforestry < complex agroforestry < coffee in semi-forest. Furthermore, while coffee trees represent the main biomass pool in monoculture systems, they only represent a small fraction of the biomass in the most complex agroforestry systems. In these diversified systems, associated trees represent the main pool of biomass.

Some of the studies also report the biomass values for non-perennial woody biomass: litter, herbaceous cover and dead wood. Specific on-farm measurements must be set up to estimate this pool of biomass as it cannot be accounted for with allometric models. It might be an important contributor to nutrient cycling in the system, but it only has an overall limited impact on the biomass balance. This biomass should not be accounted for within the LULUC balance but some emissions (other from biogenic CO_2) from residue decay may be part of the carbon footprint. Wherever it was estimated, it was lower than 10 t DM/ha, and was often the smallest pool of estimated biomass.

The figure represents biomass only (Figure 15). Although not the focus of this section, it is important to remember that soil organic carbon also represents a large pool of carbon in ecosystems. Hence, it appeared necessary to represent and compare these different carbon pools, based on the few studies that report values for both biogenic and soil organic carbon (Figure 16). Values for soil organic carbon are reported for different depths, with no harmonised protocol, complexifying the representation. The figure shows that soil organic carbon gathers most of below-ground carbon, with roughly 100 t C/ha in the first 40 cm. This carbon pool alone is substantially larger than all biogenic carbon from coffee trees in full sun monoculture and simple agroforestry systems.

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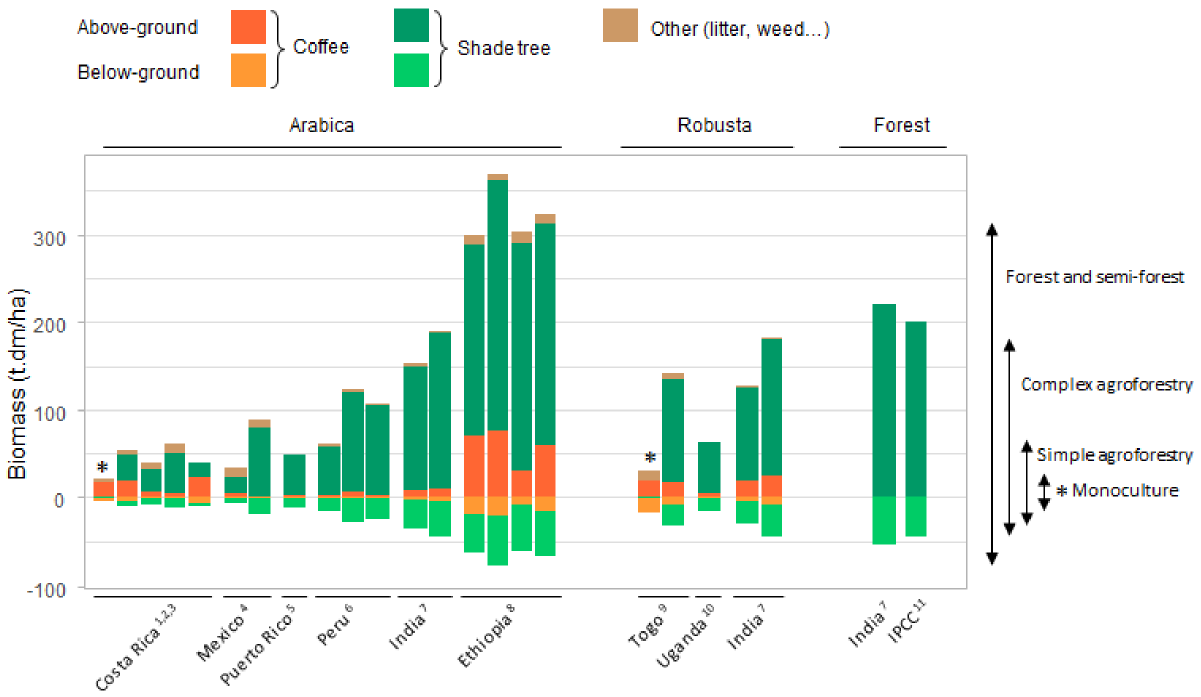
[22] https://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/Glossary_Acronyms_BasicInfo/Glossary.pdf



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1. Herguoualc'h et al. (2012)
2. Hager et al. (2012)
3. Birkenberg (2017
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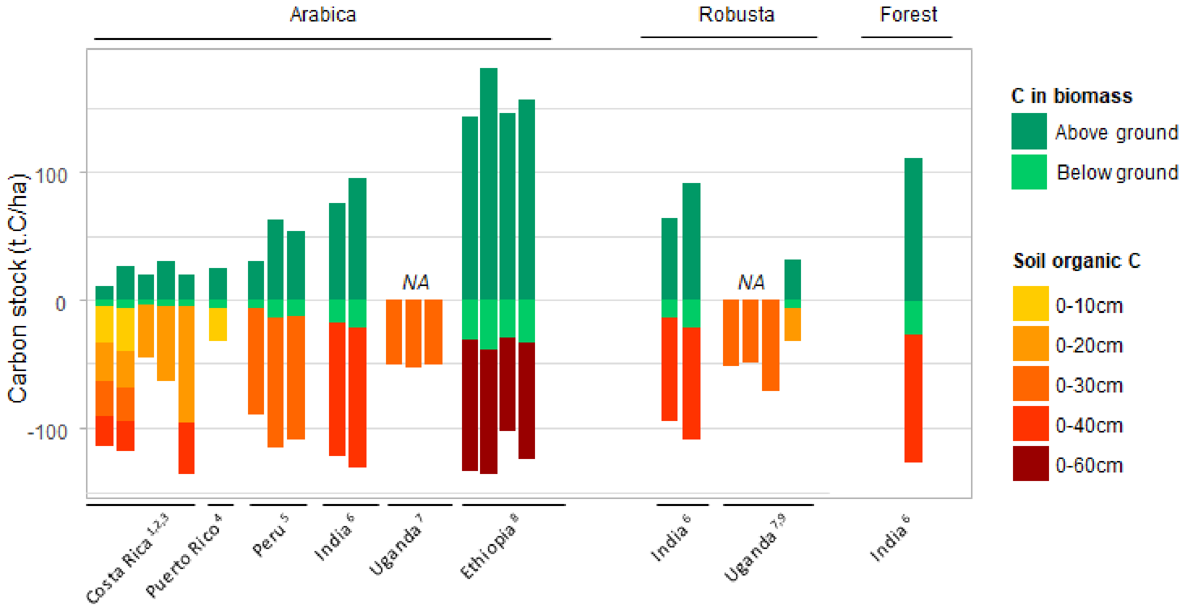
5. Lugo-Pérez et al. (2023)
6. Ehrenbergerova et al. (2016)
7. Guillemot et al. (2018)
8. Niguse et al. (2022)
9. Dosse et al. (2008)
10. Zake et al. (2015)
11. IPCC Vol 4 – typical tropical secondary rainforests (2019)

Figure 15. Biomass per unit area in various coffee systems, broken down by compartments. A typical biomass value for tropical rainforests was derived from IPCC guidelines (2019) as a comparison point, but it should be remembered that above-ground biomass in tropical forests can vary between 50 and 400 t DM/ha, while below-ground biomass can also vary in similar proportions



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5. Ehrenbergerova et al. (2016)
6. Guillemot et al. (2018)
7. Tumwebaze & Byakagaba (2016)
8. Niguse et al. (2022)
9. Zake et al. (2015)

Figure 16. Biogenic and soil organic carbon per unit area in various coffee systems

2.3.2 Co-products and waste management

Co-products can have various meanings or extents in LCA or carbon footprinting (*c.f.* glossary). In this report, in its broad sense, co-products include all other products, residues or waste produced within the considered system besides green coffee. Following a mass balance approach, considering all co-products, being valued, recycled or not, is necessary in order to avoid hidden pollution sources. Related potential impacts due to either added treatment and/or transport or direct field emissions should be fully assessed then partitioned or not depending on whether a co-product stays or exits the assessed system. Details on the recommendations regarding the quantification of emissions and inclusion or not in the carbon footprint are given in section 3. The following section proposes a state-of-the-art of potential co-products and management options in the coffee sector.

First, at the coffee plantation level, large amounts of crop residues are generated in the field due to management practices (*e.g.* crop and trees associations, pruning, etc.). For instance, it has been estimated that 32 million t of wood residues are generated annually in Brazil coffee plantations due to pruning. Moreover, despite the difficulty of estimating residual leaves biomass (due to pruning, natural or stress-induced defoliation), there are estimations of 5.5 t DM/ha being shed in Brazil, where planting densities are in the order of 4000-5000 plants/ha (Mendoza Martinez et al. 2019). It has been suggested that coffee lignocellulosic residual biomass is suitable for thermochemical conversion, as its low heating value ranges from 17.5 to 18 MJ/kg (Garcia-Freites et al. 2020), which is comparable, and even slightly higher that of most wood pellets produced from residual wood (Telmo and Lousada 2011). Even if coffee crop residues are not explicitly valorised, if left in the field they contribute to soil carbon turnover as C inputs to soil but also potentially to GHG emissions such as N_2O, which need to be accounted for. As highlighted in section 2.1, the carbon footprint of coffee plantations is often dominated by fertilisation, and occasionally heavily impacted by LUC when associated with deforestation.

Further down the chain, co-products from coffee cherries processing into green coffee (Figure 17) consist of pulp or husk, depending on the processing method: wet (full-washed) or dry, respectively. A third processing method, called semi-washed, combines elements of wet and dry processing (Sinaga and Julianti 2021). Processing separates the seed from the surrounding skin (exocarp), mucilaginous pulp (mesocarp) and parchment/hull and silverskin (endocarp), fractions that together represent ~80% of the weight of the fresh cherry (Woldesenbet, 2015). Wet processing generates as well large volumes of wastewater, as 1-15 l of freshwater are used to process 1 kg of beans (Sengupta et al. 2020). Moreover, both processes generate important amounts of residual biomass such as leaves, in the order of 5% of input raw material (Karim et al. 2019). Yields of green coffee from the three processes are estimated at 19-24% of the fresh cherry (Echeverria and Nuti, 2017; Karim et al. 2019; Rotta et al., 2021). The carbon footprint of green coffee processing is dominated by energy use and water consumption (Nab and Maslin, 2020), thus a gradient of energy use intensity is expected to be associated with the continuum of processing industrialisation intensity. For instance, Pramulya et al. (2019) suggest a cumulative energy demand for a semi-washed system in India of 3 068 MJ/t green coffee, 54% of which consists of sun energy during drying and finishing. Usva et al. (2020) studied the carbon footprint of coffee sourced from four Latin American producing countries following wet processing and consumed in Finland, finding energy consumptions between 114 and 3 110 MJ/t green coffee, depending on the level of reliance on direct solar energy and energy generation from processing residues.

Solid residues representing 55-67% of the whole cherry and liquid processing effluents representing 20-45 l per kg of beans (Sengupta et al. 2020; Laili et al, 2022), are often disposed of without further valorisation, which represents an environmental pressure in producing countries. For instance, wet processing effluents have been indicated to feature between 1200 and 35 000 mg BOD/l (Beyene et al, 2012; Laili et al, 2022). Moreover, said effluents may include agrochemical residues, high COD loads in the order of 3 000 - 15 000 mg/l, and feature pH<7 (Sengupta et al. 2020; Laili et al, 2022). Semi-washed processing liquid effluents (*i.e.* wash water), may feature higher organic loads than pulp water from wet processing (Chanakya and De Alwis, 2004). The improper disposal of solid and liquid effluents contributes to climate change, acidification, eutrophication and (eco)toxicity.

Several valorisation pathways for green coffee residues were proposed (Table 6). Among the agricultural applications of coffee pulp, as summarised in the literature (Marin-Tello et al., 2020; Serna-Jiménez et al., 2022), the following three main uses and associated pathways were identified:

- As organic fertiliser: composting with or without inoculation with *mycorrhizae*, vermicomposting, and co-composting with other agricultural residues.
- As organic amendment: application of composted or raw pulp in combination with legumes and/or *mycorrhizae*, towards mechanical improvement, phytoremediation, or stabilisation of trace elements.
- As a source of substances (vinegar, proanthocyanidin, raw pulp) for biological control.

Green coffee residues feature variable content of carbon, but often around 50% FM, with values for pulp ranging from 30 to 60% FM, and those for husks from 42 to 60% FM. Gross calorific value of husks (dry route) ranges between 19 and 25 MJ/kg DM (https://phyllis.nl/), and that of pulp (wet and semi-washed routes) is ~14 MJ/kg FM (Twinomuhwezi et al. 2021). Nitrogen content in both fresh and composted husk and pulp are in the order of:

- raw pulp 2.23% N (Netsere and Takala 2021)
- composted pulp 1.39 (1.0-2.3)% N (Netsere and Takala 2021; Fatmawati et al. 2022)
- raw husk 1.71 (0.7-2.9)% N (Netsere and Takala 2021, https://phyllis.nl/)
- composted husk 1.15% N (Netsere and Takala 2021)

Composting of pulp and husk has been amply identified as a key pathway for agricultural valorisation (*e.g.* Kassa et al., 2012; Marin-Tello et al., 2020; Nguyen et al., 2013), yet alternative valorisation strategies also exist (Marin-Tello et al., 2020; Serna-Jiménez et al., 2022): biological control, animal feed, human food, feedstock for biorefineries, feedstock for energy. Composting emissions can drastically vary between 0.03 and 129 g CH_4/kg substrate, depending on the composting technology, the ratio of green coffee residues to co-substrate and other conditions, yet they remain lower than those from open field deposition (San Martin Ruiz et al, 2018, 2021).

Coffee management practices vary highly across producing countries. For instance, synthetic fertilisers are seldom used in Ethiopia and Uganda, while in Colombia there are efforts to substitute it with organic fertilisers produced on-farm by composting processing residues (Dawid, 2018). One key product (that can be produced from coffee husks) occasionally applied in coffee systems is biochar, widely promoted towards improving soil properties and SOC sequestration (Duku et al., 2011; Hansson et al., 2021). The benefits of biochar application to coffee nurseries has been explored (*e.g.* Herviyanti et al., 2020), including its phytosanitary effects (*e.g.* Suci Rahayu and Puspita Sari, 2017).

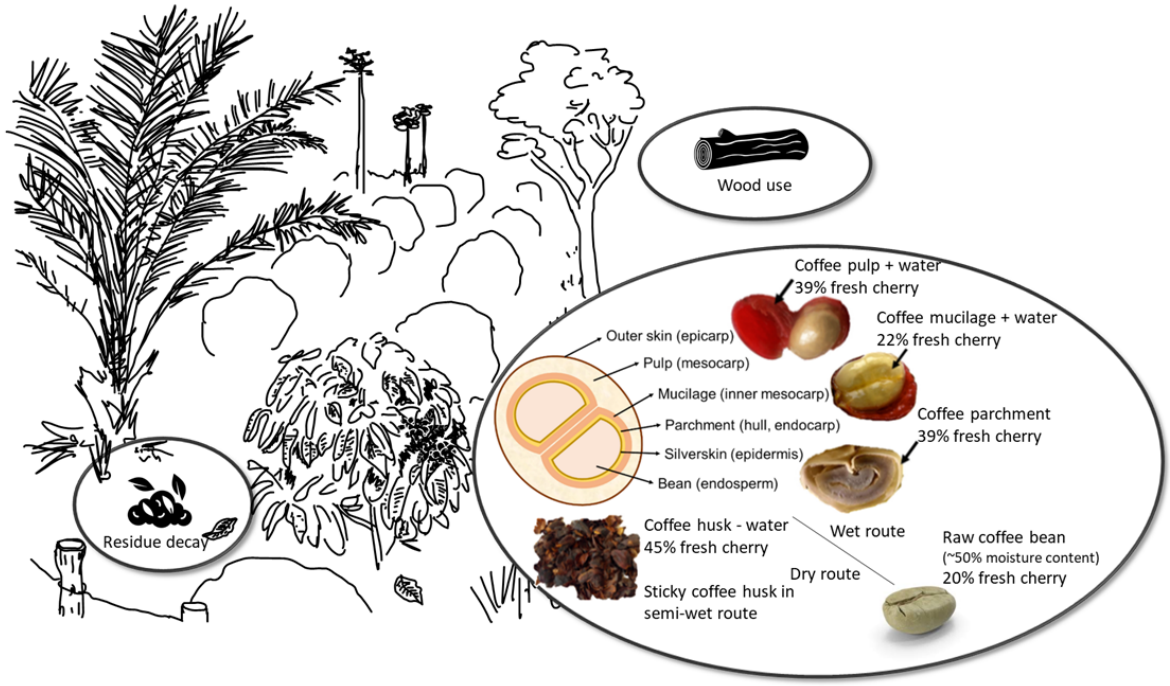

Figure 17. Overview of main co-products from an agroforestry coffee plantation. Source: adapted from Oliveira et al. 2021

Table 6. Residual streams and possible management in processing

Stages	***Waste stream, flux sources***	***Possible uses / treatment***
Plantation stage → Coffee pruning residues	Litter	• Default use: soil replenishment • Firewood or biochar production
Plantation stage → Leaf/litter all plants (coffee and associated ones)	Litter	• Default use: soil replenishment
Plantation stage (agroforestry) → Thinning (shade and non-shade trees)	Litter	• Default use: soil replenishment • Firewood or biochar production • Timber wood
Wet processing → Pulping: Removal of skin and some of the pulp by pressing the fruit by machine in water through a screen	Wastewater	• Direct emission to surface water or soil • Filtering and recirculation: washing/pulping waste water • Ponds/lagoon/constructed wetland: wastewater and reuse in agriculture • Anaerobic digestion
Wet processing → Ferment-and-wash or machine assisted wet processing (mechanical demucilaging): removal of rest of pulp and mucilage (slimy substance surrounding the parchment)	Wet residue of pulp and mucilage	• Direct application on plantation as fertiliser • Composting and application on or off farm • Livestock feed, biofuel, energy recovery, growing mushrooms, production of citric acid and natural aromas, gasification, ethanol production (pre-treatment needed in most cases)

Stages	***Waste stream, flux sources***	***Possible uses / treatment***
Wet processing → Hulling: the parchment layer (hull) and the silverskin are removed by dehulling machine	Hulls	• Biofuel, energy recovery, gasification, livestock feed, growing mushrooms, producing a moulded article from coffee bean hulls
Dry processing	Husks	• Mulch • Biofuel • Production of citric acid • Extraction of natural aroma compounds
Semi-washed processing	Husks, wet residue of pulp	• Livestock feed

Sources: Chanakya and De Alwis (2004), del Castillo et al. (2019), Echeverria and Nuti (2017), Sevenster and Verhagen (2010), Sinaga and Julianti (2021), Carvalho et al. (2011)

2.3.3 Insights on biochar use and potential

Biochar production and application from non-valorised coffee residues might be of interest to mitigate GHG emissions and/or for agronomic purposes. In this section, we reviewed the existing literature on the GHG balance of biochar production and application, the technological processes to produce biochar from coffee residues, and the agronomic impacts of the application of biochar in coffee plantations.

2.3.3.1 GHG balance of biochar production and application

Biochar involves transforming plant biomass into a product similar to charcoal. The biomass is pyrolysed (heated to between 350 and 900 degrees Celsius in an oxygen-free atmosphere), which radically changes its chemical composition. Its chemical structure becomes highly aromatic (McBeath & Smernik 2009), making it difficult for microorganisms to break it down. This material also has reactive surfaces that bind strongly with mineral surfaces, reducing its accessibility to micro-organisms (Singh et al. 2014). This material can then be brought to agricultural soils where its resistance to microbial degradation allows carbon storage over centuries, even millennia (Singh et al. 2012). In addition to these carbon storage capacities, biochar has been shown to modify ecosystem properties such as soil fertility and resilience or pollution remediation. The effectiveness of biochar in storing carbon over the long term and its co-benefits have drawn attention towards its large-scale application, with some successes, but also potentially significant feedback problems that are still poorly understood.

The ability of biochar to store carbon effectively over the long term depends on the balance between the amount of carbon lost to the atmosphere during its production (and application) and the amount and duration of storage of organic matter in the ecosystem. During the pyrolysis process, a large proportion of the carbon is lost, as the carbon and oxygen present in the organic matter react and form CO_2 until the oxygen source is exhausted. This generally represents more than 50% of the organic matter. If a positive mass balance of carbon is to be achieved in biochar production, this means that the remaining carbonaceous material must remain in the environment for much longer to compensate for the losses that occur during pyrolysis, which generally takes several years or even decades (Woolf et al. 2010). Understanding the residence time of biochar in the environment (*i.e.* the time it takes for the material to be transformed into CO_2 or CH_4) is therefore essential for assessing its effectiveness. There is strong scientific consensus that the mean residence time (MRT) of biochar carbon in soil is higher than that of all other organic carbon compounds (Coppola et al., 2018; Wang et al., 2012,2016b). Wang Lee et al. (2016) found that biochar has a small labile C-fraction of 3%, which degrades within the first year, and a large recalcitrant C pool of 97% with an MRT of 556 years. Therefore, the large recalcitrant fraction can contribute directly to long-term C sequestration in soil. However, on the basis of current knowledge, if the application of biochar appears to be effective in storing a large quantity of carbon, it is not possible to say precisely for how long and with what long-term consequences for agro-ecosystems (Schmidt et al. 2021). However, these authors stated that no negative agronomic or environmental effects have been consistently demonstrated, so far, for any of the parameters evaluated regarding performance (*e.g.* yield) and environment.

Regarding other GHG emissions (CH_4, N_2O) related to the application of biochar, Schmidt et al. (2021) highlighted, that due to the high variability and insufficient robustness of the studies, it is currently only possible to speculate on the reasons for a potential increase or decrease in soil-borne CH_4 emissions. However, it should be noted that agricultural methane emissions only reach climate-relevant levels in flooded soils such as in rice cultivation, on former peat soils with near-surface water tables or after heavy and extended rainfall events. Therefore, it should not be of high concern for coffee plantations. On the contrary, the reduction of soil nitrous oxide emissions through biochar amendment is one of the best-documented effects of its use. According to Schmidt et al. (2021), there is a clear consensus that biochar soil application reduces agricultural N_2O emissions. However, further research on the permanence of N_2O emission reduction is still needed because the vast majority of field studies primarily measured emission reduction in the first year after application only.

2.3.3.2 Technological processes to produce biochar from coffee residues

Coffee husks and residues from pruning of coffee bushes can be valuable sources to produce biochar if not already valorised by other processes. As mentioned in the previous section, coffee husk is the main by-product of the dry method and is formed by all the layers at once, including dried skin, pulp, mucilage, and the parchment (Esquivel et al. 2012). When the coffee cherry is dried, ≈12–18% of the dried fruit weight is coffee husk (Monaco et al. 1977).

Though available in large quantities throughout the years, the main application of coffee husk has been limited to composting, animal feeding or energy production. Most of the coffee husk is disposed of in landfills or arable land, usually with no care of its fate and changes to the source of pollution, especially in developing countries (Hoseini et al. 2021). Coffee husk can have several re-uses, but it is important to have environment-friendly methods to change it into usable material or material to be recycled in nature because of its important content of organic matter, chemical nutrients, and secondary compounds.

Kiggundu and Sittamukyoto (2019) studied the pyrolysis parameters to produce biochar from coffee husks. Coffee husk was fed into a batch reactor and heated to temperatures 350˚C, 450˚C and 550˚C for residence times 30, 45 and 60 min in a slow pyrolysis anaerobic setting. They showed that temperature was one of the most important factors that affect the process of biomass pyrolysis. Biochar yield from coffee husks decreased when the pyrolysis temperature increased, with minimum yield of 29.9% recorded at 550˚C and maximum yield of 35.09% recorded at 350˚C. They also recorded a decrease in the yield of the biochar with the increase in the pyrolysis residence time, with biochar maximum yield of 36.87% recorded in 30 min and minimum yield of 34.07% recorded in 60 min at a constant temperature. However, in rural areas, having such controlled conditions (temperature, anaerobic) might be a challenge.

2.3.3.3 Agronomic impacts of biochar application

Biochar generally have high porosity, high surface area and surface-active properties that lead to high absorptive and adsorptive capacity, especially after interaction in soil (Joseph et al. 2010). As a result of these properties, biochar could contribute to avoiding, reducing and reversing land degradation through the following documented benefits:

- Improved nutrient use efficiency due to reduced leaching of nitrate and ammonium (*e.g.*, Haider et al. 2017) and increased availability of phosphorus in soils with high phosphorus fixation capacity (Liu et al. 2018), potentially reducing nitrogen and phosphorus fertiliser requirements.
- Management of heavy metals and organic pollutants: through reduced bioavailability of toxic elements (O'Connor et al. 2018; Peng et al. 2018), by reducing availability, through immobilisation due to increased pH and redox effects (Rizwan et al. 2016) and adsorption on biochar surfaces (Zhang et al. 2013) thus providing a means of remediating contaminated soils, and enabling their utilisation for food production.
- Stimulation of beneficial soil organisms, including earthworms and mycorrhizal fungi (Thies et al. 2015).
- Improved porosity and water-holding capacity (Quin et al. 2014), particularly in sandy soils (Omondi et al. 2016), enhancing microbial function during drought (Paetsch et al. 2018).
- Amelioration of soil acidification, through application of biochars with high pH and acid-neutralising capacity (Chan et al. 2008; Van Zwieten et al. 2010).

More specifically, the agronomic impacts of application of biochar from coffee husks were assessed in different studies. Ngalani et al. (2023) showed, in laboratory conditions (incubation) that the application of biochar from coffee husks on acid soil had a significant effect on the increase in soil pH as compared with control. Similarly, in this study, the incorporation of biochar in soil significantly increased the soil electrical conductivity as compared to control. Finally, the quantity of available P in acidic soil significantly increased when amended with biochar. Reversely, compared to control, treatment application of biochar decreased drastically exchangeable acidity as well as exchangeable Al and Fe. Domingues et al. (2017) pinpointed that the high ash content associated with alkaline chemical species such as $KHCO_3$ and $CaCO_3$ made biochar from coffee husks a potential liming agent for remediating acidic soils. They also suggested that the high Ca and K contents in coffee husk biomass could significantly replace conventional sources of K and Ca, suggesting a high agronomic value for this biochar. Besides, according to Domingues et al. (2017), high-ash biochar, such as coffee husk, produced at low-temperatures (350 and 450°C) exhibited high CEC values, which can be considered as a potential applicable material to increase nutrient retention in soil. Hoseini et al. (2021) mentioned that studies on coffee husk biochar showed improvement in soil chemical properties by increasing pH, electrical conductivity, cation exchange capacity, organic matter, total N, and available P. Dume et al. (2015) reported that the application of 15 t/ha of coffee husk biochar that had been produced at 500 ◦C temperature had positive result on soil fertility and yield.

However, as previously mentioned, the key challenge is the availability of coffee husks to produce biochar. For instance the range of production of coffee husks is 100 to 600 kg/ha of coffee plantation, meaning around 33 to 200 kg of biochar/ha of coffee plantation, which is far from the usual application rates of biochar. Therefore, residues from pruning of coffee bushes could be a more valuable source of biomass to produce biochar. Yet no specific study assessing the agronomic impacts of such biochar was found.

Besides, apart from the type of biochar, the agronomic impacts should be assessed for coffee plantation. Again, such an assessment was not found in the literature. However, some insights might be given by studies focused on the effect of biochar application in tree cultures. Thus, Thomas and Gale (2015) examined the literature on how forest trees responded to biochar's soil amendment and summarised 17 scientific publications covering 36 tree species with trials both in nurseries and adult trees. They reported a mean increase in tree growth of 41% in the treatments with biochar, compared with the control without biochar. Growth increases were particularly pronounced at early growth stages, higher in tropical than temperate climates and higher in deciduous trees than conifers, but significant for all tree species in all climates. It should be noted that biochar for tree treatments is usually applied in the root zone, usually by precise manual application. When planting a tree, the biochar substrate is then added to the planting hole, and for already established trees, it is applied either in the topsoil directly around the tree or in holes or furrows around the radius of the tree canopy where the use of low biochar doses (<2 t/ha) achieved significant yield increases.

2.3.3.4 LCA impacts of biochar production and application

There has not been, yet, LCA studies on the comprehensive impacts of biochar production and application in coffee plantations. As usual, from a life cycle perspective it is important to consider both the production of the biochar itself but also all potential activities and impact up- and further downstream.

In a recent review, Matustik et al. 2020, concluded that in spite of all the differences across studies, being contextual or methodological, there was still a clear trend that application of biochar into agricultural soil would provide significant benefits throughout the life cycle of the system. Across the reviewed LCA studies, the main source of GHG emission was the pyrolysis system itself, while the impact of transportation was usually low or marginal. In the reviewed studies, the GHG emissions caused by the biochar production and handling were always outweighed by the benefit of both carbon capture in biochar and the energy production offsets, providing that the co-products of pyrolysis such as syngas and bio-oil are recycled. However, carbon sequestration and overall agronomic benefits varied among the projects. Likewise, the impact of biochar manufacture and transport would highly depend on the context. In a scenario analysis of rice and maize productions in China with biochar application, Xu et al. 2019, highlighted how the net GHG balance varied with assumptions on the SOC storage (based on IPCC coefficients) and process co-products recycling (Figure). In another study, where those co-products were recycled, biochar transport appeared to be the only remaining GHG emission hotspot (Munoz et al. 2017).

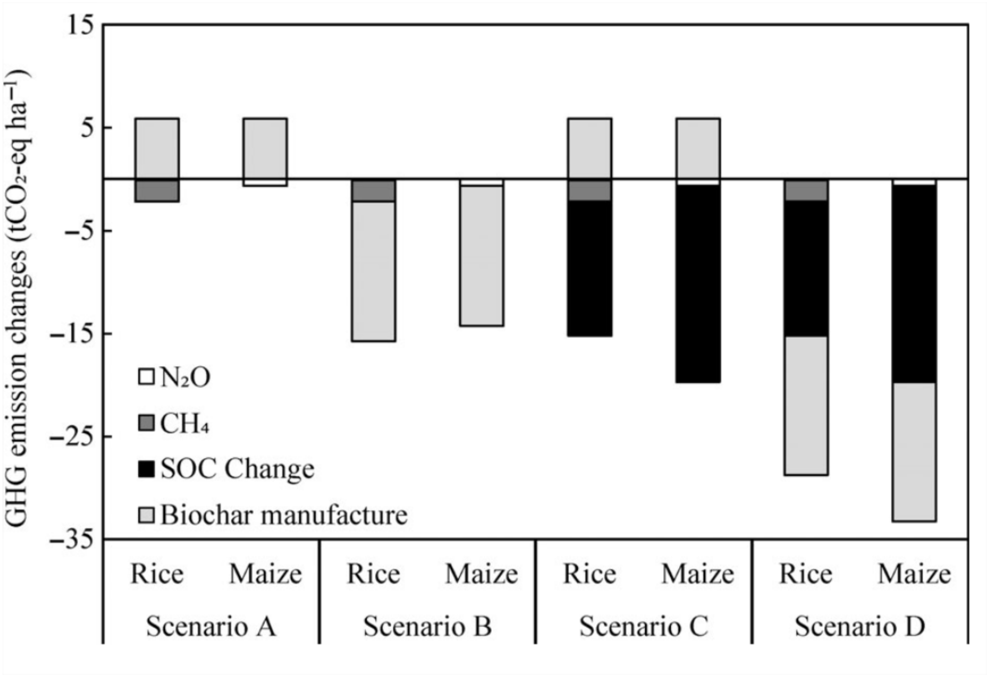

Figure 18: Scenario analysis of GHG emission changes depending on the biochar manufacture strategies and including SOC change based on default IPCC factors. Source: Xu et al. 2019

In conclusion, the overall balance depends, in chronological order, on:

1. The optimisation of the pyrolysis process and biochar supply to the field:

a. Use of optimal feedstock (including optimised biomass properties and collection logistics ahead);

b. Use of optimal temperature (energy sourced from renewables if possible);

c. Recycling of pyrolysis process co-products;

d. Minimising logistic impact for the supply and field application of biochar.

=> Besides benefits from co-product recycling, the optimisation of the pyrolysis process also leads to more stabilised biochar (Feng et al. 2020, Mohammadi et al. 2020) producing further benefits in the field.

2. The improvement of soil health and management practices:

a. Reduced use of mineral fertilisers, where nitrogen and phosphorus losses would be reduced thanks to biochar application (*e.g.* through improved water-holding capacity or phosphorus adsorption);

b. Improved pH and reduced use of liming practices and associated GHG emissions;

c. Potential soil organic carbon storage.

=> The benefits in the field depend on the soil and climate contexts and require a systemic adaptation of practices, in other words a comprehensive approach of the cropping system by adjusting all practices in terms of fertilisers, irrigation, etc., as biochar input only may not be sufficient to harness all potential environmental benefits and compensate for biochar embedded environmental costs.

3 Recommendation on the coffee carbon footprint

In view of the review of coffee LCA and methodological guidelines, we identified some gaps and provided recommendations based on updated research results and detailed guidelines compilation.

This section covers the following recommendations:

1. Sampling strategy, including typology and clustering, and data quality appraisal,
2. Perennial crop cycle modelling to account for all development stages,
3. Emission factors and databases for GHG emissions across the green coffee life cycle,
4. LULUC and estimation of carbon stock in biomass (above and below ground)
5. Co-products (residues from plot and mill) handling and wastewater management: management practices, composition and associated emission factors,
6. Reporting and communication

LCA and carbon footprint studies are strictly codified and one must rely on official guidelines to conduct any robust assessment. We recommend using the CFP-PCR for green coffee and ISO 14067 as a baseline, and to complement it with recommendations in section 3. As illustrated in Figure 18, these could be useful resources for the future update of the CFP-PCR. While this report does not substitute any existing guidelines, we aimed to provide sound information and recommendations where guidelines are not specific or detailed enough. Hence, in this section, we do not cover all exhaustive stages in LCA or carbon footprinting but rather focus on key recommendations to facilitate and improve the quality of green coffee carbon footprints.

On a side note, it is important to mention that regionalisation in LCA has been under-development for two decades with new promising development thanks to new LCA open software. Given the global scope of this study with no specific insights on some countries, this report does not explore the status of LCA regionalisation for any given specific region or country. Hence recommendations apply potentially in all coffee producing regions.

In the first section, we focus on the methodological recommendations regarding sampling strategy and overall data quality needs to carry out a proper assessment. Then, we focus on the specificity of perennial crop modelling and provide recommendations on ways to proceed, also in agreement with the following recommendations on biomass and LULUC accounting. Finally, we provide exhaustive recommendations on comprehensive ways to handle co-products and ensure sound accounting of emissions related to crop residues and processing.

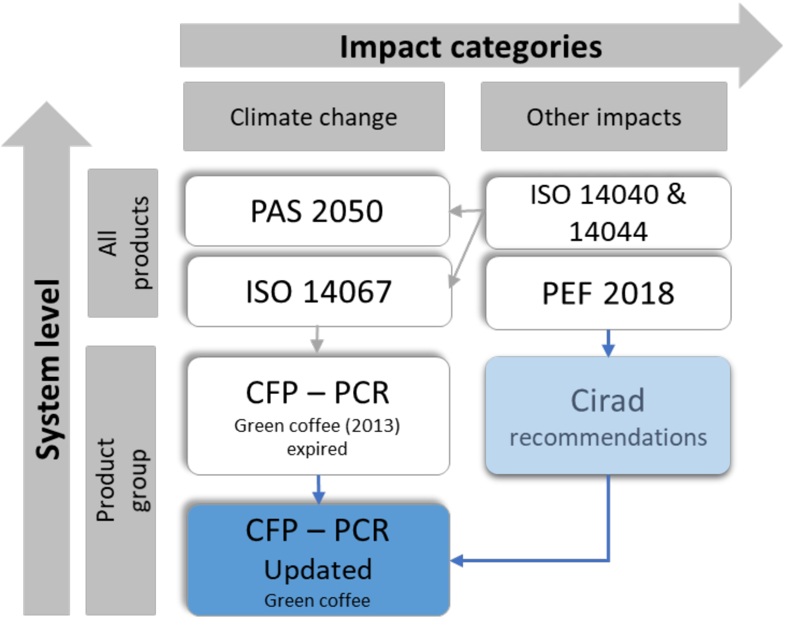

Figure 18. Recommendations in this report should be considered in the future update of the CFP-PCR for green coffee

3.1 Recommendation on the sampling strategy and data quality check

3.1.1 Sampling and typology

Choosing the sample size is dependent on the objective, the acceptable uncertainty error, the anticipated distribution in variation. Thus, the sampling protocol should rely on the best possible knowledge of the system. Before using any statistical formula (which varies slightly depending on the guideline) we recommend designing the sampling protocol on a specific typology of the farms (and the post-harvest stages).

Figure 19 provides a decision tree for the sampling protocol, including the guidelines recommendation (where relevant) and our recommendations. Below we further detail the most frequent and recommended pathway based on a system typology.

Since complete sampling is rarely feasible, the remaining sampling strategies in CFP-CPR are both based on the assumption of "homogeneous" population or cluster (*i.e.* sub-group). Homogeneous clusters need to be determined by context-relevant typologies to make sure the actual variability is captured. The cluster selection is thus critical. An expert-based typology focusing on how practices diversity affects carbon footprint results allows the identification of key variables (ex. N fertiliser input, yield…). Amongst the criteria to consider, we recommend that each cluster:

1. Must be in identical agroecological potential zones according to Global Agro-ecological Zones (GAEZ) classification[23],
2. Must fit into the same broad cropping system category: *i.e.* monoculture unshaded, monoculture shaded, polyculture or agroforestry,
3. Must use similar fertiliser type (organic/mineral) and amount (for N fertiliser in particular),
4. Must use the same 1st processing technology

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[23] https://gaez.fao.org/pages/data-viewer

Once clusters are identified, the sample size can be determined based on the square root of the full population size weighted by the supply share (CCF-PCR), or a more elaborated approach considering the variance of key parameters for each cluster (*e.g.* Kuit et al. 2020). Since N fertilisation is often a key variable, we recommend using as a default the standard deviation of kg N inputs/ha/yr.

Under time or human resources constraint, these “statistical approaches” may not be feasible. We thus propose an alternative option of sample size based on expertise, as long as it is based on a robust typology and clustering (Figure 19).

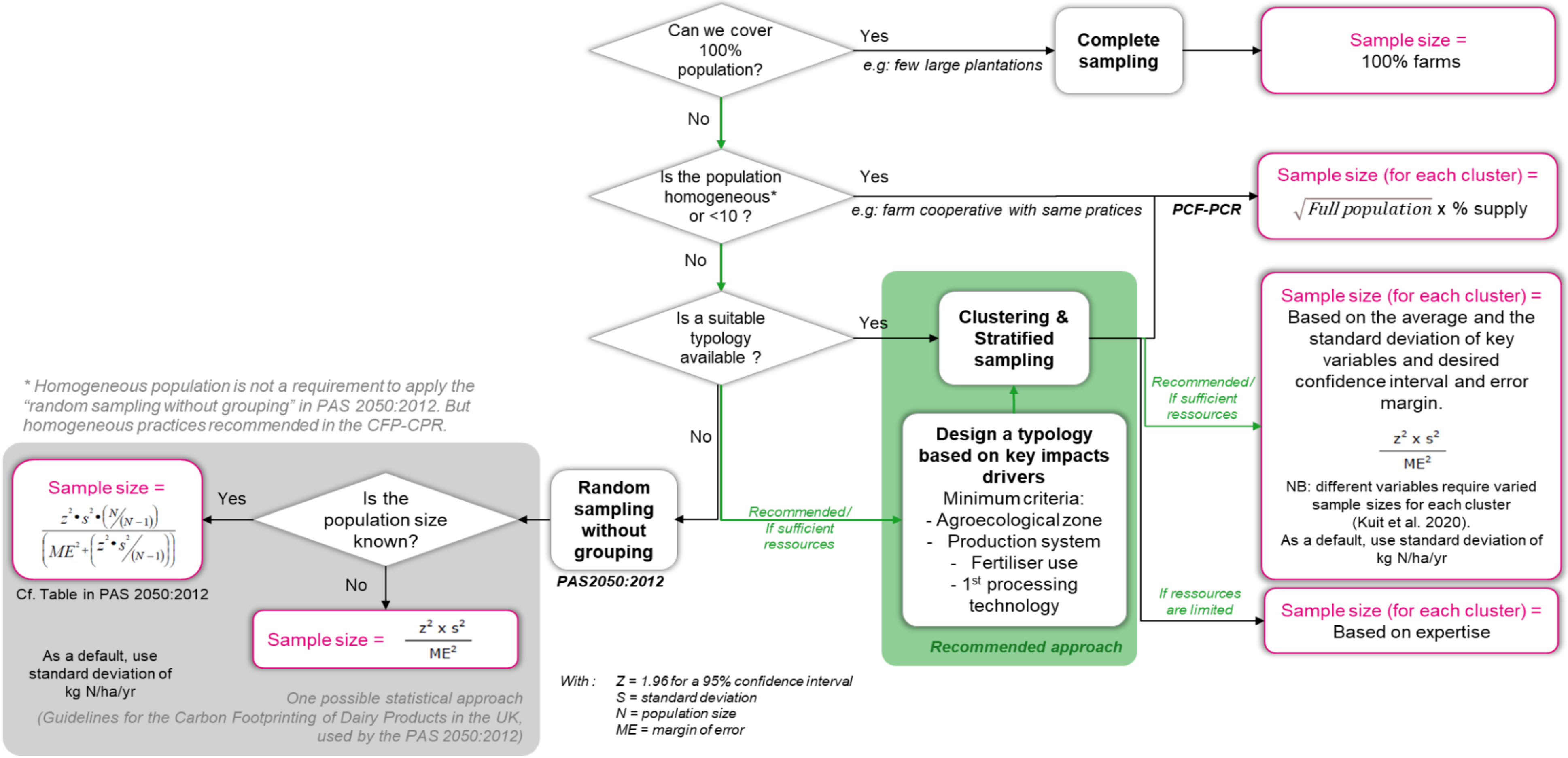

Figure 19. Decision tree for the selection of the best sampling procedure (for plantation and primary processing stages)

3.1.2 Data quality appraisal system

Qualitative diagnosis[24]

The most detailed guidance on the use of the qualitative assessment of data in LCA is provided in the latest version of the European Product Environmental Footprint (PEF) Category Rules Guidance (2018) (EC 2018[25]). The data quality rating system (DQR) consists in:

Four criteria:

- Precision (P)
- Time representativeness (TiR)
- Geographical representativeness (GR)
- Technological representativeness (TeR)

A two-tier approach to score those criteria depending on the data:

- Primary data: score for precision cannot be higher than 3 and the other scores cannot be higher than 2
- Secondary data: scores from 1 to 5

A formula to aggregate the scores (Equation 11).

$$DQR = \frac{(\overline{TeR}+\overline{GR}+\overline{TiR}+\overline{P})}{4} \qquad \text{Equation 11}$$

The scoring approach somehow mixes qualitative and quantitative information. For primary data, the qualitative assessment should be focused on the "most relevant processes and direct elementary flows that account for at least 80% of the total environmental impact". This threshold should be calculated based on process contributions to the total single score (excluding the 3 toxicity-related ones). It requires an iterative approach were LCIA results are calculated first in order to target the processes and input data to be assessed for the DQR. For all important processes and flows, as selected based on their contributions, the scores should be estimated separately, and the total DQR should be calculated based on the weighted average of the scores (*i.e.* multiplied by the contribution to the total of 80% of total impact) as shown in Eq. 11.

Precise guidelines are provided in order to estimate the scores for primary and secondary data (*c.f.* Table 7). They also explain how to combine scores from primary and secondary data for elementary flows (EF), activity data (AD) and secondary data (SD).

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[24] As detailed in https://doi.org/10.35690/978-2-7592-3467-7

[25] EC (2018) Product Environmental Footprint Category Rules Guidance v6.3.

Table 7: Abstract (two first scores) from PEFCR guidance on "how to assign the values to DQR criteria when using company-specific information?"

Score	PEF and PAD	TiR-EF and TiR-AD	TiR-SD	TeR-EF and TeR-SD	GR-EF and GR-SD
1	Measured/calculated and externally verified	The data refers to the most recent annual administration period with respect to the EF report publication date	The EF report publication date happens within the time validity of the dataset	The elementary flows and the secondary dataset reflect exactly the technology of the newly developed dataset	The data(set) reflects the exact geography where the process modelled in the newly created dataset takes place
2	Measured/calculated and internally verified, plausibility checked by reviewer	The data refers to maximum 2 annual administration periods with respect to the EF report publication date	The EF report publication date happens not later than 2 years beyond the time validity of the dataset	The elementary flows and the secondary dataset is a proxy of the technology of the newly developed dataset	The data(set) partly reflects the geography where the process modelled in the newly created dataset takes place
…	…	…	…	…	…

PEF: Precision for elementary flows; PAD: Precision for activity data; TiR-EF: Time Representativeness for elementary flows; TiR-AD: Time representativeness for activity data; TiR-SD: Time representativeness for secondary datasets; TeR-EF: Technology representativeness for elementary flows; TeR-SD: Technology representativeness for secondary datasets; GR-EF: Geographical representativeness for elementary flows; GR-SD: Geographical representativeness for secondary datasets.

In order to comply with the regulatory PEFCR, all details on the DQR assessment should be provided, including the quantitative contributions. This approach is very comprehensive and constitutes robust information on qualitative assessment of an LCA study. Alternatively, a PEFCR-DQR based qualitative assessment could be more rapidly done by LCA authors, based on their expert-judgement on process and flows contribution and providing non-weighted DQR scores. Such a simplified approach may be a first step in data quality assessment but would not consist in full PEFCR compliance.

The data quality assessment done at each inventory flow level, without weighting and aggregation is the first step in applying the pedigree matrix.

Uncertainty approximation with Simapro software 1-5 score implemented

In ecoinvent databases, an uncertainty factor (expressed as a contribution to the square of the geometric standard deviation) is attributed to each of the score of the data quality criteria (Frischknecht et al. 2007; Weidema et al. 2013). In the version v.3.0, five criteria are considered with five levels of score (see ecoinvent 3.0 pedigree matrix in Ciroth et al., 2016). The total uncertainty accounts for a basic uncertainty based on expert knowledge (and varying depending on the type of input/output) and the cumulated uncertainty factors related to the five scores, which were recently updated based on several datasets compiled by Ciroth et al. (2016) (see Empirically based uncertainty factors for the pedigree matrix in ecoinvent v.3.0).

3.2 Recommendation on the perennial crop cycle modelling

Perennials, such as coffee trees, differ from annual crops in many aspects arising from their long-term development. Perennial long and partitioned cycles (*e.g.* immature, then mature phases) imply specific management usually combining long-term management strategies and short or medium-term adjustments. It also implies complex and evolving interactions with the ecosystem that affect the potential performance of the crop and the efficacy of the management. Indeed, management feedback on the production may be delayed due to the long-term development of the agroecosystem and may be more or less direct depending on the harvested product (*i.e.* biomass from *Miscanthus × giganteus* versus cherries from coffee trees). Assessing perennial crops in the same way as annual ones may hence induce an important bias notably due to the variability in practices and yields over the plantation lifespan or the potential importance of long-term changes in carbon stocks (Mithraratne et al. 2008). Beyond the scientific logic behind the whole perennial crop cycle modelling, at sector as well as individual levels, a comprehensive modelling is also key to be able to monitor management effects and track changes over several years. Annual-like modelling might vary drastically from one year to another due only to changes in perennial crop phase or delayed feedback, which may produce confusing results.

Recent reviews highlighted the need to better account for the specificities of perennial cropping systems within LCA and to harmonise the way LCA of perennial crops is conducted (Bessou et al. 2013; Cerutti et al. 2013; Cerutti et al. 2011). Studies also exemplified bias in results due to varying choices in modelling the perennial crop cycle within LCA (Bessou et al., 2016), including in the specific case of coffee *in* Trinh et al., 2020, as discussed in section 2.1. However, guidelines are not precise enough yet regarding the modelling of perennial crops within the LCA framework. Based on recommendations published by Bessou et al. (2013), we propose to apply a modular approach to model the perennial cropping system as detailed below.

The modular approach consists in a weighted average of each key development phase of a perennial cropping system depending on its duration over the complete cycle. The modular approach only concerns the plantation within the coffee process chain up to green coffee. For each phase, considered as a module, a data set of at least 2-3 continuous years should be compiled to also account for yearly climate variability. Those datasets should be compiled to compute a mean yearly inventory for each phase. The minimum recommended number of development phases for coffee plantations is 3 (Figure 20):

1. The immature or vegetative phase, when production is null, not yet profitable or too random (*i.e.* output set to zero);
2. The mature or productive phase - first stage, when production is steadily increasing;
3. The mature or productive phase - second stage, when production is about stable and up to the plantation potential;
4. The senescing phase (optional), when production starts to decline slowly but irremediably (may or may not occur depending on the intensity of the farming system, notably the frequency of replanting).

Depending on data availability and the plantation dynamics, more sub-phases or sub-modules may be defined. The more the better but following the parsimonious principle; *i.e.* each added sub-module should be justified by physiological and productive significant changes across sub-modules. Moreover, a more sophisticated modelling of various sub-modules is only worth it if primary data is available.

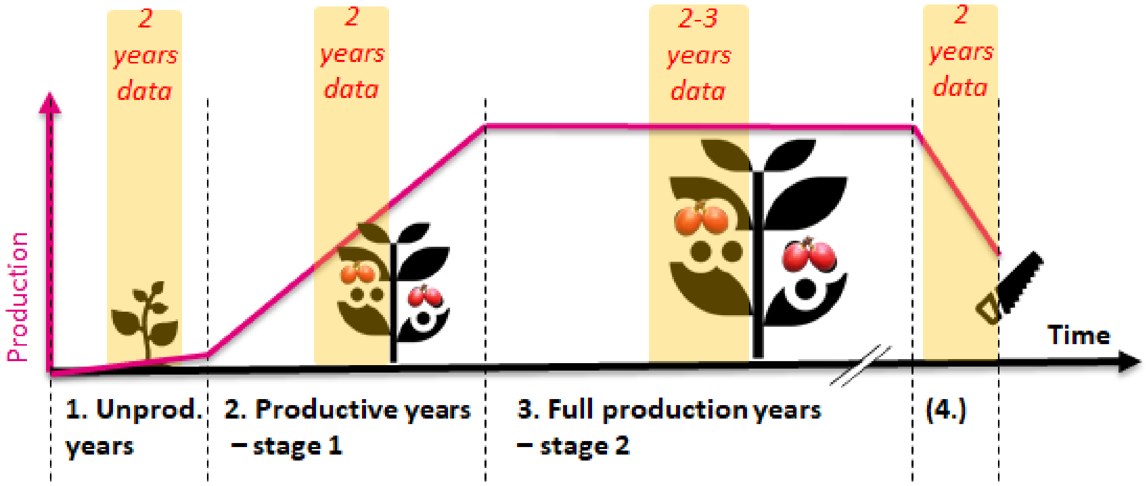

Figure 20. Inputs/outputs data should be collected for at least 2 years of each development phase, also called module, then averaged over the whole cycle based on each module duration or weight

According to the modular approach data would be computed according to equations (12 & 13). These equations refer to one perennial plantation over a fixed land use area (*e.g.* 1 ha). Equation (12) provides the weighted average annual elementary flows of 1 ha plantation when integrating the whole cycle. It could hence provide the result in the case of a FU of 1 ha plantation. Elementary flows in LCA refer to all inputs and outputs, used materials and emitted substances, at each unit process of the product supply chain. The LCI is the list of all elementary flows that are summed up and characterised to calculate the impacts. In a complete LCA, the weighted annual averages should be computed for all elementary flows. In the case of carbon footprint, elementary flows only concern the inputs to the plantation that lead to GHG emissions on- and off-farm (*e.g.* sum of GHG emissions due to the manufacture, transport and field application of nitrogen fertilisers) and waste. Equation (12) needs to be divided by the weighted average annual production over the whole cycle, when the FU is in mass of output, *e.g.* kg of green coffee. In this case, the equation (13) is simplified with the total crop cycle length cancelled out.

$$\frac{\sum_i^n mean\ yearly\ elementary\ flows_{phase\ i} \times years_{phase\ i}}{Total\ years\ of\ a\ full\ cycle}$$

Equation 12

$$\frac{\sum_i^n mean\ yearly\ elementary\ flows_{phase\ i} \times years_{phase\ i}}{\sum_i^n mean\ yearly\ green\ coffee\ output_{phase\ i} \times years_{phase\ i}}$$

Equation 13

$with\ n = number\ of\ development\ phases\ or\ modules$

Equation (13) stresses that the longer the immature unproductive phase, the higher its contribution as the numerator increases but not the denominator. On the other hand, if the overall plantation duration is increased, the contribution of the immature phase and other fixed costs is reduced, so is the averaged result as long as the production does not decrease. Likewise, if inputs are stopped near the end of the cycle, *e.g.* senescing phase, but that some production goes on, the denominator increases and not the numerator.

The application of the modular approach can be challenging when little information is available on past years or in the case of very young plantations with no perspectives on expected development and performance. There are, however, ways to overcome such obstacles:

- A same producer may have several plantations in different development phases within similar or close-enough pedo-climate and management contexts. Information from such plantations can be concatenated to produce a comprehensive composite data set (interpolation). Likewise, if young trees are mixed up with older ones through partial replanting, varying managements according to tree ages may be found and recorded within a given plantation;
- Scenario analysis can be used to test various options of potential future developments (extrapolation), and scenario results may be then averaged. In all cases, such scenarios are as uncertain as modelling LCA only based on a partial cycle. However, at least one scenario is very likely to be right, whereas with partial modelling the only result is very likely to be wrong. The use of scenario analysis is also interesting to highlight how potential development may affect the carbon footprint and which options should be pursued as far as possible;
- Ultimately, secondary data from literature may be used to model one or more sub-models (approximation).

When facing these challenges, one should test with a sensitivity analysis how assumptions influenced the modelling outputs and where largest uncertainties arose.

The estimation of each module duration depends on the plantations specificities and should be defined *ad hoc* by the carbon footprint assessor based on primary data (*e.g.* farmer's survey). The plantation lifespan can greatly vary across regions, cropping systems and management intensities. For instance, full-sun monoculture coffee plantations may only last a decade or so (*e.g.* in Brazil), whereas old agroforestry plantations may still be producing after 50 years (*e.g.* in Angola). Also, the intensity of trimming, pruning or replanting will affect the average duration of coffee tree lifespan and phases within this lifespan.

The average duration of each stage should be defined at the plantation level, smoothing out variability among trees, *i.e.* some may grow more or less quickly and be more or less productive, as well as integrating the replanting strategy, *i.e.* the average age of coffee trees when they are replaced. In some plantations, variability may be high due to pathogens or non-homogeneous quality of seedlings, or for other many reasons. Also, replanting may be hampered or fostered by many factors such as costs or changes in management strategies. In practical terms, the average durations of phases may not be computed on exhaustive records of individual tree histories or prospective futures but rather on rough estimates based on farmers' knowledge and cross-checks with records (*e.g.* expenses for replanting) and/or field visits. Over the whole plantation lifespan, within a given finite land area (*i.e.* as long as there is no expansion of the used land area), depending on the intensity and frequency of the replanting, trees of different ages will co-exist. The weighted average of all phase averages enables the integration in a snapshot of the perennial dynamics in both temporal and spatial dimensions (Figure 21).

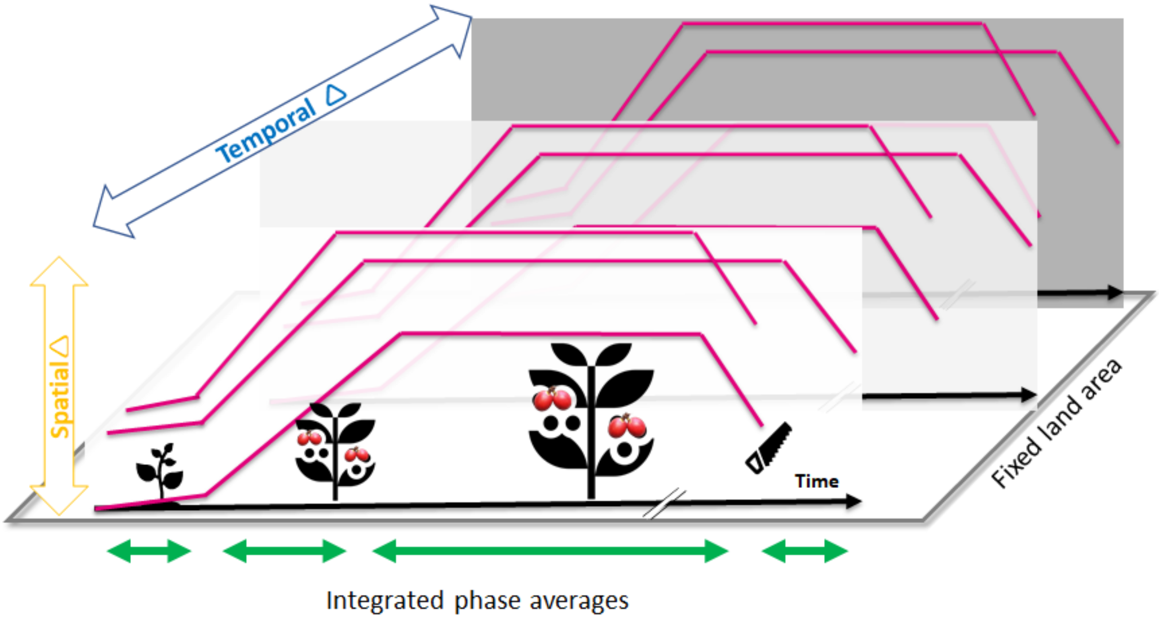

Figure 21. The average durations of each development phase over the whole coffee plantation should be computed accounting for the variability across the plantation due to the individual tree heterogeneity and/or replanting frequency

Further specifications:

- Land preparation and uprooting/end of life of the plantation shall be accounted for and considered as fixed costs amortised over the full cycle. In practical terms, those fixed costs are added to Equation (13) numerator, implicitly considering a one-year timeframe. Land preparation for the first plantation cycle may require more energy input than when establishing a second plantation cycle;
- Although the nursery stage would usually also be included in LCA of perennial cropping systems, it may be excluded from the green coffee carbon footprint as its contribution would be negligible for the global warming impact indicator, which would be not true for other impact indicators such as water depletion or human toxicity (*e.g.* Cabot Lujambio et al. 2023, Bessou et al. 2016). The nursery stage should be included, though, in the following cases:
    - Nurseries in greenhouses;
    - Coffee plantations with high planting density (>5000 seedlings/ha) or a plantation lifespan <10 years, and intensive nursery management with numerous inputs including an automatic irrigation system.
- Other associated perennials (crops or trees) that would be considered within the coffee system due to interactions (*i.e.* shade service) should be modelled also based on a modular approach, where the modules and the durations would be adapted to the other perennial specificities. The nursery stage for associated trees with a long lifespan of several decades should not be included. Associated perennials that would be managed completely independently from the

coffee trees (*i.e.* fruit trees with no interaction with the coffee trees) might be kept out of the coffee system boundaries and not further investigated.

Perennial cycle modelling with a modular approach

Concept: weighted average of all inputs-outputs by key development phases based on their respective durations over the full cycle.

The development phases, also called modules here, may be defined (number and duration) by the assessor depending on the coffee plantation specificities and/or prospective scenarios.

As much as possible, primary data (*e.g.* specific field data for a given plantation) should be recorded and used. Where data is missing, one may i) extrapolate from another similar plantation managed by the same farmer or group of farmers, ii) interpolate existing data with prospective scenarios, or, at last resort, iii) approximate data based on secondary data from literature.

In all cases of challenging data collection, a sensitivity analysis on main parameters (*e.g.* varying phase durations, varying yield evolutions or input demands…) should be carried out to check how uncertainties propagate up to the final results.

3.3 Recommendation on LULUC and biomass accounting

3.3.1 Accounting for coffee plantation biomass within the frame of LULUC

There are four steps in LULUC assessment:

1. Determining whether there has been LUC or not linked to a given coffee plantation;
2. Calculating the LUC total impact;
3. Amortising the LUC impact;
4. Apply steps 2 and 3 in the case of carbon stock changes within a given land use (LU) “remaining in the same land use category”, *i.e.* no LUC.

Although the first stage would seem the most obvious because the farmer should be aware of what the land use was before planting the coffee trees, it is not. The main reason lies in the subjective choices made by the scientific community, notably in the field of attributional LCA, that are not systematically applied consciously.

In a long-term perspective, in any given land area, land uses may have changed many times over the years, *e.g.* from native vegetation to grassland up to urban built area, eventually. The drivers for LUC can hardly all be defined nor prioritised. At a given point in time, the simplest solution may be to only consider the last immediate direct land use change (LUC), providing that any past previous LUC impact had been already accounted for (*i.e.* paid off or amortised). IPCC recommended the 20-year timeframe as a minimum delay for natural regrowth on average globally[26] (excluding irreversible impacts such as biodiversity losses). So, if a land use stays unchanged for at least 20 years, it may regrow to some original point if left abandoned or kept in a constant applied land use state. In both cases, past LUC is considered paid off and there is no more LUC to consider. This 20-year span, although being continuously discussed, has got a lot of implications in LCA modelling.

As land area is a finite resource, another complexity dimension arises when determining further indirect drivers for LUC linked to the connected pressure across various land resources. Within the LCA framework, however, indirect LUC should only be accounted for in consequential LCA since it is considered as a rebound effect. In practice, though, some indirect LUC may be also included in attributional LCA.

Step 1: Determining whether there was LUC or not linked to a given coffee plantation

Considering the previous paragraphs, one needs to look at 20 years back to check for LUC or continuous land use. Either the farmer has the historical record of the past 20 years of the coffee plantation land area or a national average can be used. Looking at national data on comprehensive land uses enables us to identify which types of land uses have gone through area increase or decrease over the investigated time period. If a crop, *e.g.* coffee, is among a land use category (*i.e.* perennial crops) whose overall land area has increased, then this increase percentage will be accounted for as LUC share within the coffee plantation (Figure 22). This procedure was originally recommended by PAS2050 based on IPCC guidelines, then implemented in various guidelines such as the GHG Protocol or the Blonk tool, which implements global FAO data to compute LUC. Statistical data for 3 to 5 years is usually also averaged on each end of the 20-year span to smooth out yearly variability. The reference to land use “categories'' such as arable land or forest land was originally linked to the IPCC guidelines (first editions in 1996), where a land use change was defined as a change from one land use category to another one; *i.e.* a change from one arable crop to another one was not considered as LUC. Also, at the national level, the analysis by land use category is easier.

On the one hand, one can notice that the national average approach cannot identify shifting cultivation, whereby LUC may occur while the total crop area may stay stable but moved around various land areas (it is not an issue in the case of long-term perennials such as coffee plantations which cannot be easily moved around over short time periods). On the other hand, the national average approach encompasses both direct and indirect LUC within a given country at the land use category level. For instance, if coffee land area increases, as well as the perennial total land area, meanwhile forest land area decreases. Part of the deforestation will be allocated to LUC to coffee, even though the directly observed LUC may have been “forest to maize” somewhere and “maize to coffee” somewhere else within the same country, which would be defined as indirect LUC.

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[26] IPCC notes that it would be longer in temperate and boreal systems, although it is the default.

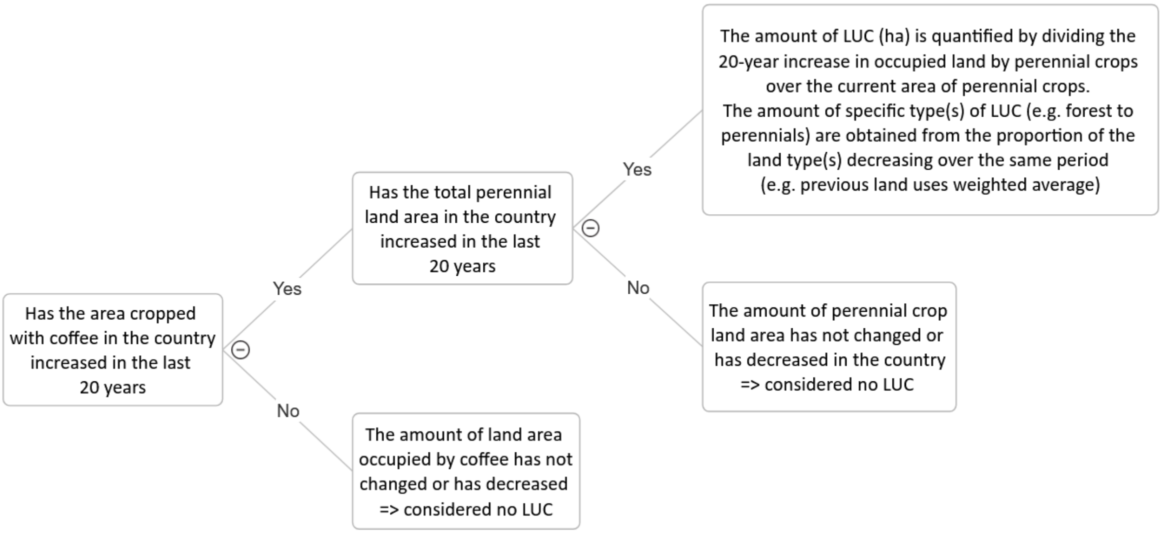

Figure 22. Decision tree to identify LUC based on national average when historical record for a given coffee plantation is missing. Source: adapted from Mila i Canals et al. 2012

Step 2. Calculating the LUC total impact

We recommend applying the IPCC Tier 1, stock difference method (2006), which is the most commonly applied and aligned with the 20-year timeframe[27] (Eq. 14). The principle lies in comparing two "stabilised" carbon stocks in two land uses. The 20-year timeframe is considered as the minimum duration to reach "stabilisation" in agreement with the previously developed argument.

It is important to stress i) IPCC guidelines are related to GHG only, therefore the assessment of LUC impacts based on IPCC is only partial as it does not look at biodiversity losses nor models irreversible impacts; ii) the 20-year timeframe may be relatively correct for the bulk of above-ground biomass globally but it is relatively incorrect for carbon stocks that take longer to build up, notably soil organic carbon; finally iii) the IPCC guidelines mentioned that longer time period than the 20-year default may be used in other Tier approaches, if justified. However, the default value ensures consistency across studies and a longer time period would increase the risk of untraced or unamortised LUC.

$$\Delta C_{stock\ from\ LU1\ to\ LU2} = \frac{A \times (Cstock_{LU2} - Cstock_{LU1})}{\Delta t} \qquad \text{Equation 14}$$

$with:$
$\Delta C_{stock} = carbon\ stock\ difference\ in\ a\ given\ land\ area, A, due\ to\ LUC\ from\ LU1\ to\ LU2$
$\Delta t = timeframe\ to\ account\ for\ LUC\ is\ 20\ years\ by\ default\ in\ IPCC\ Tier\ 1$
$Cstock_{LU} = sum\ of\ all\ carbon\ pools\ in\ above\ and\ below\ ground\ biomass, dead\ wood\ pool\ and\ litter, and\ SOC$

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[27] "20 years is the time period assumed for carbon stocks to come to equilibrium for the purposes of calculating default coefficients in the 1996 IPCC Guidelines and retained for GPG-LULUCF and used here also, though other periods may be used at higher Tiers according to national circumstances" *In* IPCC 2006, Vol 4, Chapter 2, p13/59

IPCC guidelines provide carbon stock values by default but which are hardly coffee and site-specific. All carbon pools should be accounted for, including above and below ground biomass, dead wood and litter, and soil organic carbon (SOC). Dead wood and litter are usually considered as null given their fast turnover (except for forest with >30% canopy closure). Considering all these carbon pools does not mean that the full sum of those stocks will eventually face the same fate as it depends on the land clearing process (*e.g.* burning or not). The fate of the stocks and emissions are discussed below.

The IPCC default carbon stock values could be used for other land uses, but for coffee plantations we recommend relying on the biomass review presented in this report (*c.f.* section 3.3.2). IPCC default carbon stock values were estimated at maturity or after 20 years, whichever the earlier. For coffee plantations, we recommend to use carbon stocks that are time-averaged over the plantation cycle. First, time-averaged carbon stocks are aligned with the perennial crop cycle modelling (*c.f.* section 3.2). Second, time-averaged carbon stocks account for the succession of cycles, which enables a more consistent comparison with very old stands such as natural forests. As described in section 3.2 for the perennial crop modelling, time-averaged carbon stocks account for the different development phases, which lead to various biomass and carbon accumulations, and those accumulations are weighted by the varying phase durations along the crop cycle. Time-averaged carbon stocks were proposed by ICRAF in the late 90s with an example on coffee plantation (*c.f.* Annex 1).

When comparing carbon stocks in tropical forests with those in different types of coffee plantations (Figure 23), one can grasp the potential importance of LUC emissions and the importance of the compared time dimensions. From a global perspective, land areas all have an original stock, therefore cumulated carbon stocks in human made landscapes may not come at no cost. Where a few original trees may be kept in an agroforestry plantation (grey trees in complex agroforest on fig indicated with an arrow), the initial stock right after LUC may not be zero and the overall time-averaged stock may stay above that of less complex systems such as monoculture unshaded. In the stock difference, those kept trees will reduce the difference as their stocks were not lost nor gained. When shade trees are planted together with the coffee trees, their stocks will also matter both in quantities and in the duration of their stocks.

The total carbon stock will depend on both the planting densities of coffee trees and associated trees, and the duration of the different growth phases. Carbon stocks in annual crops are not accounted for due to their too short lifetime. Most parts of annual crops are rapidly exported and used, the rest usually decomposing within a year or two. Hence, if a coffee plantation is established after an annual crop land, the LUC consists in an increased net carbon storage. In full sun coffee plantations with or without associated crops, the overall carbon stock will not be directly modified by the carbon stock in associated annual crops that is too short-lived. However, the net carbon stock may be influenced by the coffee planting density with relation to that of the associated crops and eventual competitions for resources and growth.

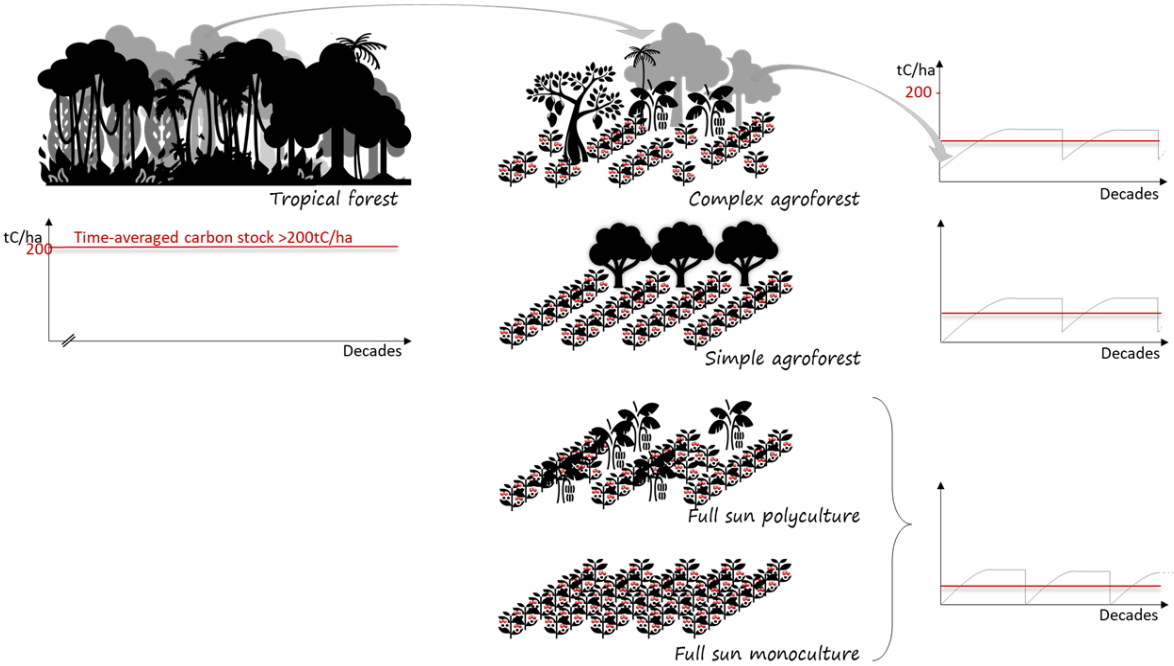

Figure 23. Framework for LUC accounting where time-averaged stocks are compared between tropical forest and various types of more or less complex coffee plantations.

Once the stocks are calculated for a given LUC scenario, to compute the stock difference, emissions "from" *LU1,* the cleared land use stock, need to be determined and subtracted from the potential storage "to" *LU2.* If information is available on the land clearing process, primary data should be prioritised. In other cases, the IPCC-based default table provided by ecoinvent V3.0 et reused by WFLDB V3.0 is recommended (Table 8).

Although the characterisation of LUC was first focused on carbon stock changes, emissions related to the release of some carbon pools are not limited to C-based GHG only. In particular, N-based GHG may be also released with relation to C/N components in the biomass and SOC. The release process will also influence the emission profiles, as the gas profiles vary when burning compared to decaying, or when decay occurs in aerobic or anaerobic conditions. Emission factors depending on the release process and C/N default values depending on the biomass sources are provided by IPCC (2006). On the contrary, for the increase in stock to *LU2*, only CO_2 sequestration is considered as the capture of other biomass compounds such as N does not come from atmospheric GHG but other gases without radiative forcing (*e.g.* N_2, NH_3). Given the long timeframe (at least 20 years), emission and sequestration of biogenic CO_2 are not considered as neutral.

As a side note, in annual crops as mentioned before and in Table 8 dead organic matter is considered null within the frame of LUC, *i.e.* the biogenic CO_2 from crop residues decaying is considered as neutral. It is consistent with the other pools containing biogenic CO_2 not considered as neutral given their longer residence time in the biomass. However, it is important to bear in mind that other GHG from crop residues decaying are to be accounted for in the carbon footprint as part of the annual LCI and not within the LUC accounting framework.

Table 8. LUC from crop production follows the methodology applied in ecoinvent V3.0 (Wernet et al. 2016), which is based on IPCC (2006) methodology

Carbon pool	Land transformation				
	From primary forest	From secondary forest	From perennial crop	From annual crop	From grassland
AGB (1)	8% harvested and stored 92% emitted (20% burned, 72% by decay)			100% emitted by decay Net carbon capture may occur in certain cases (and is taken into account)	
BGB (2)	100% emitted by decay				
DOM (3)	100% emitted by decay			Ignored	
SOC (4)	SOC change according to IPCC 2006, including peat drainage emissions. Net carbon capture may occur in certain cases (and is taken into account)				

(1) Aboveground biomass; (2) Belowground biomass; (3) Dead organic matter; (4) Soil organic carbon

Step 3. Amortising the LUC impact

The time frame is key to identify LUC and amortise it, both are intrinsically connected. So, IPCC 2006 guidelines recommend a linear amortisation over 20 years. The implementation of this 20-year amortisation has different meaning, though, depending on the starting point. When looking straight backwards for a LUC 20 years ago[28], the 1/20 of LUC impact (emission or sequestration) is somehow meant to be the final share (19th) of the specific LUC 20 years ago and then this assumption is checked year after year of assessments. However, some amortisation years may be missed depending on the starting point of the assessment Figure 1 and a cross-check with plantation age and/or first establishment year is necessary. Using the actual 20-year historical record (*e.g.* based on primary data or remote sensing classifications) can help to model LUC amortisation more consistently. On the other hand, when accounting for known LUC that has occurred recently, the 20-year amortisation supposes that the 1/20 of LUC impact should be allocated to the many years of future continuous land use until amortisation is completed. Consistently, on the 21st year of a continuous land use, when looking 20 years back there is no more LUC to consider.

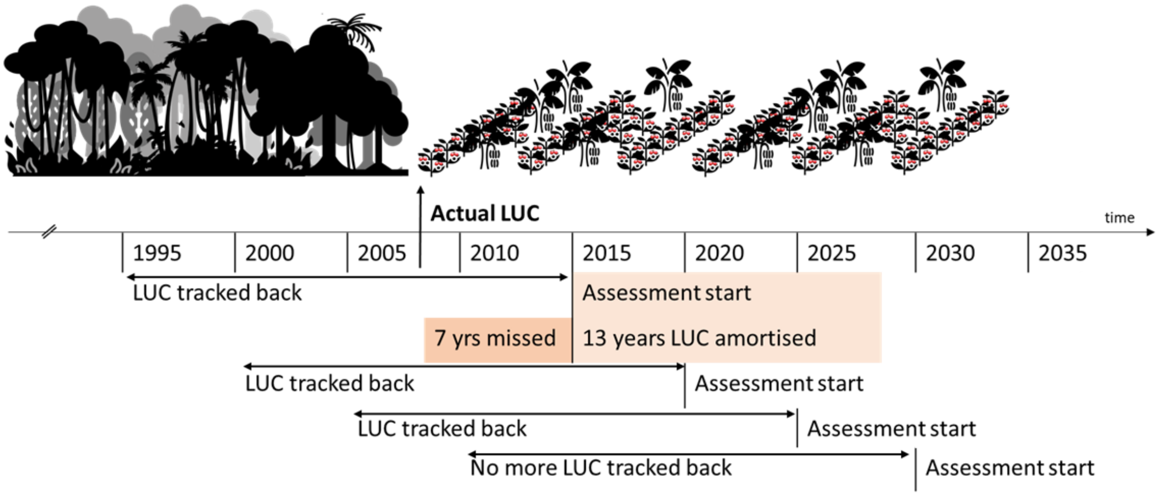

Figure 24. LUC amortisation depending on the assessment starting date

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[28] See Figure 24 as recommended by various guidelines when direct data on LUC is not available. Such an approach may be only robust at a national level, whereby all land use resources are considered across many sec

In all cases, modelling the full perennial cycle provides some guardrails. First, it requires being aware of the cycle starting point and duration. Second, it implies an amortisation over the whole cycle, whereby doubt about future completion of LUC amortisation may not arise. For plantation duration around 20-year (±2-3) lifespan, the perennial modelling does not create distortion compared to the baseline 20-year IPCC default. For plantations with shorter turn-over around 10-year (±2-3), we recommend amortising the LUC impact over two cycles, which is the minimum duration to consider LUC and which is consistent with time-averaged stocks over the cycle. For plantations older than 20 years (±2-3), no more LUC should be accounted for anyway. In order to check how amortisation choice affects the final result, we recommend testing the 20-year amortisation period (*i.e.* adding 1/20 LUC impact to the result calculated over the whole cycle) in a sensitivity analysis and displaying both results.

Amortisation of LULUC impact should be consistent with allocation rules at the plantation level. In particular, in the case of associated tree-crops together with coffee, which may also store some biogenic carbon for at least 20 years, either the whole storage potential of a given area is allocated to coffee or it is split between tree-crops depending on the allocation rules defined for the study. For instance, if fertiliser environmental burdens are allocated to various tree-crops within the coffee plantation according to their respective needs (*c.f.* Section 2.2), the potential LULUC impact should be also allocated to the various tree-crops based on the same rules. In such allocation cases, both results with and without allocation should be displayed.

Step 4. Land use remaining in the same land use category

Once LUC impact has been amortised and there is not anymore land use category change, *i.e.* land use remaining in the same land use category, IPCC 2006 guidelines provide the same recommendations in terms of carbon stock variations. As long as changes occur over a sufficient period of time to reach a new steady state (*i.e.* always 20 years by default), carbon stock variation can be computed following the stock difference equation Eq. 5, *i.e.* applying steps 2 and 3 for long-term changes from one coffee plantation type to another one. For instance, if an old complex coffee agroforest (>20 years old) is replaced by a coffee full sun monoculture, carbon stock changes will lead to net GHG emissions. It would go the other way, *i.e.* net sequestration, when changing from full sun monoculture to simple agroforest. Again, accounting for the full perennial cycle is needed to try and ensure, as far as possible, that the time frame is consistent with long-term management changes that do consistently affect the carbon stocks. As detailed in section 3.3.1, more knowledge and data are still needed to properly model all stock changes, especially regarding SOC stocks. By default, IPCC (2006) proposed various tillage and input weighting management factors that can be used to model long-term changes in SOC around the soil type and climate defined standard SOC_{ST} and within a given land use category (*i.e.* perennial crops in the case of coffee).

3.3.2 Biomass estimation for coffee plantations

In the case of LULUC, biomass stocks need to be estimated based on the plantation specificities. The estimation of a coffee plantation biomass relies on a set of parameters to model the main aspects of the farming system design and management (mainly planting densities and duration of rotations), and allometric equations and default factors to model the different perennial components of the farming systems (the different species and their biogenic carbon).

For simple and complex agroforestry systems, associated trees represent the largest pool of perennial woody biomass. Efforts should be made to quantify this pool in the most detailed possible manner, as it will have the most influence on the overall biomass and carbon estimation. Numerous allometric models exist to quantify the above-ground biomass of associated trees from simple measurements in the coffee plantation. Note that we discourage the use of allometric models with tree age as the main input variable, due to high levels of uncertainties. The types of allometric models are listed below, from the most to the least specific:

- (Developing) species-specific and site-specific models for associated trees. These models can have either tree shape parameters (height, DBH, basal area) or tree age as input variables to characterise growth, considering that growth is sufficiently homogeneous in the study area.
- (Using existing) species-specific models for associated trees. These models can only use tree shape parameters (height, DBH, basal area) as input variables to characterise growth.
- (Using existing) default models for groups of associated tree species.

Before using any model, one must first ensure that the model yields outputs within the proper orders of magnitude, both at the individual tree level and at the stand level (after multiplication with tree density). It is not uncommon to find models returning unrealistic values; those must be discarded.

Considering the difficulty of estimating the below-ground biomass of associated trees, the majority of studies use multiplicative coefficients, known as root-to-shoot ratios, to derive the below-ground biomass from the above-ground biomass. These coefficients were developed for forestry, not for agricultural systems, and are therefore only used in agricultural systems due to the absence of more specific data. For tropical and subtropical forests, the root to shoot ratio ranges in the IPCC guidelines between 0.24 and 0.42, while according to Cairns et al. (1997), the root to shoot ratio would range between 0.23 and 0.34. Except if there are species-specific and/or site-specific data available on below-ground biomass, we recommend following the same approach.

Finally, the biomass estimated at tree level must be multiplied by tree densities to get the above-ground biomass at the stand level. It is important to check, at this stage, that the values of biomass obtained for the coffee plantations are lower than those of forested areas found nearby. Furthermore, one should not forget that this method based on allometric equations returns biomass estimation for trees of a certain size or age, but that the global footprint of the coffee plantation must consider the whole duration of the plantation, and the time-averaged biomass estimation across this duration (Figure 23).

The above method focuses on the perennial woody biomass and forgoes the non-perennial and non-woody components of the system, such as leaf, leaf litter, herbaceous cover, and dead wood. These pools are time consuming to measure and often only have small contributions to the overall biomass balance of the system. Furthermore, they are assumed to decompose rapidly while emitting biogenic carbon dioxide, and should therefore not be accounted for in LCA and carbon footprints.

Recommended default allometric models for biomass of associated trees, in the absence of species-specific models

Above-ground biomass

- fruit trees with DBH ≤ 30cm: Andrade (2008) / Somarriba (2013)
    - AGB (kg DM/tree) = 0.0776 * DBH (cm) ^ 2.64 AGB of fruit tree (kg DM/tree) = 0.0776 * DBH (cm) ^ 2.64 Equation 15
- other trees and fruit trees with DBH > 30cm: Chave (2014) or other default model
    - AGB = 0.0673 * (q * DBH ^2 * H) ^ 0.976 Mixed species: AGB = 0.0673 * (q * DBH ^2 * H) ^ 0.976 Equation 2
    - where q is the wood density (g/cm^3)

Below-ground biomass

- IPCC guidelines or Cairns (1997)
    - 0.23 ≤ Root-to-shoot ratio ≤ 0.42

Orders of magnitude

- Above-ground biomass at tree level
    - DBH = 10 cm => AGB_fruit ~ 30 kg DM/tree | AGB_other ~ 20-30 kg DM/tree
    - DBH = 15 cm => AGB_fruit ~ 100 kg DM/tree | AGB_other ~ 50-80 kg DM/tree
    - DBH = 20 cm => AGB_fruit ~ 200 kg DM/tree | AGB_other ~ 90-170 kg DM/tree
    - DBH = 25 cm => AGB_fruit ~ 380 kg DM/tree | AGB_other ~ 140-300 kg DM/tree
    - DBH = 30 cm => AGB_all ~ 200-470 kg DM/tree
- Above-ground biomass of associated trees at stand level
    - Simple agroforestry: AGB ~ 30-100 t DM/ha
    - Complex agroforestry: AGB ~ 50-300 t DM/ha
    - Above-ground biomass of agroforest ≤ Above-ground biomass of local forests
- Below-ground biomass
    - ~ 30% of above-ground biomass

The biomass in coffee trees constitutes the second pool of perennial biomass in coffee agroforestry systems, and the first one in full sun systems. Similarly, to shade trees, the estimation of above-ground biomass is done with the use of allometric equations. Numerous allometric models were developed for Arabica coffee, allowing the use of models adapted to various ranges of application (dwarf or non-dwarf cultivar; short or long rotations). On the other hand, few models were developed for Robusta coffee.

Below-ground biomass of coffee trees is seldom studied and one of the important knowledge gaps. Overall, based on the few studies available, the use of a coffee-specific root-to-shoot ratio can provide a rough estimate of the biomass of coarse roots. This low level of accuracy might still be enough to estimate the overall biomass at the plot level, especially in agroforestry systems, where coffee trees only represent a small fraction of the biomass.

Here again, one should not forget that methods based on allometric equations returns biomass estimation for coffee trees of a certain size (and therefore age), but that the global footprint of the coffee plantation must consider the whole duration of the plantation, and the time-averaged biomass estimation across this duration.

Recommended allometric models for biomass of coffee

Above-ground biomass of Arabica coffee

- Dwarf cultivars managed through regular pruning and stumping, with stem diameter below 8 cm: Andrade (2018).
  - AGB (kg DM/tree) = 0.36 - 0.18*D(cm) + 0.08*D^2 Equation 10
  - D is measured at 40 cm from the ground or above the stump
- Non-dwarf cultivars planted at low densities (< 2,500 tree/ha): Guillemot (2018)
  - AGB (kg DM/tree) = 0.0048 * (pi*D)^2.06 * PCA^0.525 Equation 11
  - D is measured at 30 cm from the ground
  - The projected crown area (PCA) in m^2 is deducted from planting density (PCA ~ 4 m^2 for a planting density of 2,500 trees/ha)
- Very large and old arabica trees, *i.e.* taller than 5 m and with stems larger than 8 cm. These are often found in old forests and homegardens: Negash (2016)
  - AGB (kg DM/tree) = 0.147*D^2 Equation 12

Above-ground biomass of Robusta coffee

- Single peer-reviewed reference: Guillemot (2018)
  - AGB (kg DM/tree) = 0.0177*π*D*PCA^0.818 Equation 20
  - With D the stem diameter (cm) at 30 cm from the ground
  - With PCA = projected crown area (m2) that can be derived from the planting density.

Below-ground biomass

- Root-to-shoot ratio for coarse roots of either Arabica or Robusta
  - R = 0.40

Orders of magnitude

- Above-ground biomass of Arabica coffee
  - 0 kg DM/tree ≤ AGB ≤ 5 kg DM/tree (for most common arabica coffee varieties, but can go higher for wild coffee trees)
  - 1 t DM/ha ≤ AGB ≤ 20 t DM/ha (with most common estimates between 5 and 10 t DM/ha)
- Above-ground biomass of Robusta coffee
  - 5 kg DM/tree ≤ AGB ≤ 25 kg DM/tree for a mature tree
  - 5 t DM/ha ≤ AGB ≤ 20 t DM/ha for a mature plantation
- Below-ground biomass of Arabica & Robusta
  - ≤10 t DM/ha for coarse roots (≥ 2 mm)
  - ~10-20 t DM/ha for all roots (including ≤ 2 mm) in a mature plantation

A clear gap of knowledge was found regarding the assessment of the belowground biomass in coffee plantations while this pool could account for between 20 and 100 % of the above-ground biomass. Therefore, there is a need to carry out additional studies with robust methodology (see Defrenet et al. (2016) in a variety of coffee systems (*i.e.* monoculture, agroforestry, etc.).

Similarly, based on our review, we found that SOC stocks in coffee plantations can account for a considerable amount of carbon that would need to be better assessed. SOC stocks are impacted by land-use, land management but also environmental parameters (*e.g.* soil type, climate). Therefore, a comprehensive review of the literature related to coffee plantations would be an asset to improve the accounting.

Additionally, in section 2.3, we reviewed the existing literature on biochar for coffee plantations. The following recommendations can be proposed:

- A long-term assessment of the impact of the application of biochar on GHG emissions would be necessary as the vast majority of field studies primarily measured emission reduction in the first year after application only.
- Development of field experiments with biochar application as most of the studies were carried out in laboratory conditions (incubation). These experiments would be crucial to assess the agronomic impacts of biochar application in coffee plantations in soil and climate specific contexts
- A huge need to characterise the biochar from residues from pruning of coffee. Indeed, residues from pruning of coffee bushes could be a valuable source of biomass to produce biochar, yet no specific study assessing the agronomic impacts of such biochar was found.
- Assessment of the LCA impacts of biochar production and application for coffee production as no comprehensive studies encompassing the biochar production and its application in coffee plantations was found. Besides, as indirect benefits in the field depend on the soil and climate contexts and require a systemic adaptation of practices, such assessment should be context-dependent.

Specific recommendations for calculation method can be found in the IPCC Appendix 4 from 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, “Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments: Basis for Future Methodological Development”[29].

3.4 Recommendation on emission factors

We recommend using *a minima* default disaggregated emission factors from the latest IPCC report (2019) and LCI from the most recent ecoinvent dataset (Wernet et al. 2016), currently version 3.9.1 released in December 2022. Table 9 and Table 10 provide detailed recommendations for each activity across the green coffee life cycle.

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[29] https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch02_Ap4_Biochar.pdf

Table 9. Recommended emission factors per activity and GHG emission flow. This table does not consider emissions from organic soil (or peatland), in the case of such a plantation, annual GHG emissions at ha level should be added based on IPCC 2013 Wetlands supplement.

Activity	***GHG emission***	***Recommended modelling approaches / emission factors***	***Reference***
Fertiliser and pesticide manufacture	Background GHG	Supplier-specific fertiliser (type, composition), "Market" process for the origin) LCI from database	most recent ecoinvent dataset "Market, cut-off" (v 3.9.1)
Transport (off-farm)	Background GHG	Specific transport (type, size, age/EURO type) LCI from database Transport distance: actual inland distance transportation for the final transport from store to the plantation unless site-specific data not available, use "Market" processes for inputs	most recent ecoinvent dataset "Market, cut-off" (v 3.9.1)
Transport (foreground)	Foreground GHGs	Specific transport (type, size, age/EURO type) LCI from database Transport distance: Primary data	most recent ecoinvent dataset "Market, cut-off" (v 3.9.1)
Electricity use for farm operations and 1st processing	Foreground GHGs	Country-specific electricity mix LCI from database	most recent ecoinvent dataset "Country mix, cut-off" (v 3.9.1)
Fuel use for farm operations and 1st processing	Foreground CO_2	If site-specific data is not available, use proxy from database (*e.g.* average tractor fuel use)	most recent ecoinvent dataset "Market, cut-off" (v 3.9.1)
Fuel combustion for farm operations and 1st processing	Foreground CO_2	Emission factors for air emissions from Diesel combustion	SAEFL 2000 cited by Nemecek 2007
Fertiliser application (Urea and lime)	Direct field CO_2	Default Tier 1 emission factors: Limestone: 0.12 kg CO_2-C / kg limestone Dolomite: 0.13 kg CO_2-C / kg dolomite Urea: 0.20 kg CO_2-C / kg urea	IPCC 2006 Volume 4 Chapter 11 (no refinement in 2019)
Fertiliser application (synthetic & organic), crop residues, N mineralised	Direct field NO_2	Default Tier 1 EF1 disaggregated by climatic zone and fertiliser type [kg N_2O–N / kg N]: · Synthetic fertiliser inputs in wet climates: 0.016 · Other N inputs in wet climates: 0.006 · All N inputs in dry climates: 0.005	IPCC 2019: Volume 4 Chapter 11 Table 11.1
	Indirect field NO_2 (associated with volatilised & re-deposited N + N lost via leaching/runoff)	Default Tier 1 disaggregated (if available) or aggregated emission, volatilisation and leaching factors > summarised in Table 10	IPCC 2019: Volume 4 Chapter 11 Table 11.3

Activity	***GHG emission***	***Recommended modelling approaches / emission factors***	***Reference***
Wet process fermentation	Foreground CH_4: Biogenic methane emissions from coffee pulp decomposition	It shall be assumed that 5% of the Carbon content in pulp is emitted as CH_4 (see Table 12) Total C-content in pulp is 93.3 kg C/t green coffee when assuming 576 kg cherry pulp/tonne green coffee beans, 70% water in coffee cherries and 54% C in coffee cherries (FNC, 2015). Other proportions of pulp to cherry are proposed in the literature (see Table 12)	Hermann, 2011 cited by PCR Moka and Espresso
Co-products (*e.g.* pruning residues, wastewater…)	Foreground GHGs	Cf. Table 11 and Table 12	

Table 10. Default Tier 1 emission, volatilisation and leaching factors for indirect soil N_2O emissions, adapted from IPCC 2019 Volume 4 Chapter 11 table 11.3 (only disaggregated value -if available- are provided here)

Emission factor	***Disaggregation***	***Disaggregated (if available) or aggregated value***	***Unit***
EF $_4$: N volatilisation & redeposition	Wet climate [1]	0.014	kg N_2O-N / (kg NH_3-N + NO_x-N volatilised)
	Dry climate	0.005	
EF $_5$: leaching/runoff	N/A	0.011	kg N_2O-N / (kg N leaching/runoff)
Frac $_{GASF}$: volatilisation from synthetic fertiliser	Urea	0.15	(kg NH_3-N + NO_x-N)/ (kg N applied)
	Ammonium-based	0.08	
	Nitrate-based	0.01	
	Ammonium-nitrate-based	0.05	
Frac $_{GASM}$: volatilisation from all organic N fertilisers applied	N/A	0.21	(kg NH_3-N + NO_x-N) / (kg N applied or deposited)
Frac $_{LEACH-(H)}$: N losses by leaching/runoff in wet climates	N/A	0.24	kg N /(kg N additions or deposition by grazing animals)

Notes: [1] Wet climate occurs in temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration > 1, and tropical zones where annual precipitation > 1000 mm. Dry climate occur in temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration < 1, and tropical zones where annual precipitation < 1000 mm (*c.f.* Figure 3.A.5.1 in Chapter 3 of Vol. 4 IPCC 2019 provides a map subdividing wet and dry climates based on these criteria)

There is a need to develop farming system-specific emission factors in the given soil-climate context. IPCC (2019) Volume 4 Chapter 11 suggests the emission factor could be further disaggregated as part of a Tier 2 method. This disaggregation could be based on 1) environmental factors (soil organic C content, soil texture, drainage, soil pH and climate such as temperature and freeze-thaw cycle), and 2) management-related factors (N application rate per fertiliser type; fertiliser type, liquid or solid form of organic fertiliser; irrigation and type of crop).

3.5 Recommendation on added needed data and experimental trials

3.5.1 Data requirement and emission factors for wet process (and associated co-products and waste)

Solid waste

Recommended approaches are summarized in Figure 25.

METHANE:

1. Specific coffee pulp deposition / composting methane EF from San Martin Ruiz (2021):

- Open field deposition (large piles of fresh coffee pulp buried for several years) => EF = 360 g CH_4 / kg of coffee pulp / year. Up to 2160 g CH_4 / kg of coffee pulp.
- Composting of coffee pulp alone => EF = 129 g CH_4 / kg of coffee pulp
- Composting of coffee pulp mixed with ≥ 20% green co-products (based on volume) => EF = 22.7 g CH4 / kg of coffee pulp.
- Other composition or treatment> use IPCC 2019: Cf. below

2. If solid waste composition or treatment not covered above, use IPCC 2019 kg CH4 = f(DOC; MCF) for:

- Direct application of coffee pulp in coffee farm, spread close to coffee
- Composting coffee husk instead of coffee pulp (following the natural process)

> with DOC based on specific measurement or the default value:

Degradable organic carbon (DOC) => we assume that it is similar to "total carbon loss during composting in lab-scale reactors & static piles" => for food waste, DOC = 54% (Ye et al. 2023)

> with MCF selected from Table 3.1. in IPCC 2019 V5 Ch3 (Cf. below)

IPCC 2019 - V5 Ch3 – Methane emissions:

Methane emission estimate is based on the amount of decomposable degradable organic carbon (the part of the organic carbon that will degrade under the anaerobic conditions) = product of the fraction of degradable organic carbon (DOC in kg C/kg), the fraction of the DOC that decomposes under anaerobic conditions (DOCf), and the part of the waste that will decompose under aerobic conditions (prior to the conditions becoming anaerobic, which is interpreted with the Methane Correction Factor MCF).

Combining equations 3.2 and 3.3 from IPCC 2019 gives:

kg CH4 = DOC * DOCf * MCF * F * 16/12

- Use specific DOC (kg C / kg) values. If not available, use default for food waste, DOC = 54% from Ye et al. 2023
- If DOCf values are not available, use DOCf = 0.7 for highly decomposable wastes, e.g. food wastes, grasses (garden and park waste excluding tree branches). Other default values for other waste components with different degree of biodegradability in Table 3.0.

- MCF default values for various performance of landfill aeration in table 3.1, ranging from 0.4 (unmanaged shallow or active aeration) to 1 (managed and anaerobic) > Select MCF value based on your system
- F fraction of CH_4 in generated landfill gas (volume fraction) default value F = 0.5
- 16/12 = molecular weight ratio CH4/C

Example: Under unmanaged shallow / active aeration conditions:

kg CH_4 = 0.7*0.4*0.5*16/12* DOC = 18% DOC

NITROUS OXIDE:

For N_2O emissions during field application, use IPCC 2019 kg N_2O = f(N content)

> with N content based on specific measurements

> or coffee-specific parameters for N content:

Coffee Pulp (San Martin Ruiz 2021):	Coffee husk (Nguyen 2013):
Total N content: 2.3% of dry matter	Total N content: 1.27%
Total N content of final coffee compost from coffee pulp: 1.3% of fresh mass	Total N content of final coffee compost from coffee husk: 2.1% of fresh mass

IPCC 2019 - V4 Ch11 – N_2O emissions (Table 11.1):

kg N_2O = kg N * EF N_2O * 44/28

- With EF N_2O [kg N_2O-N/kgN)] N in crop residues & organic amend = 0.006 (0.001 – 0.011) for wet climate and 0.005 (0 – 0.011) for dry climate
- kg N: Use specific N content value or based on San Martin Ruiz 2021, Nguyen 2013.

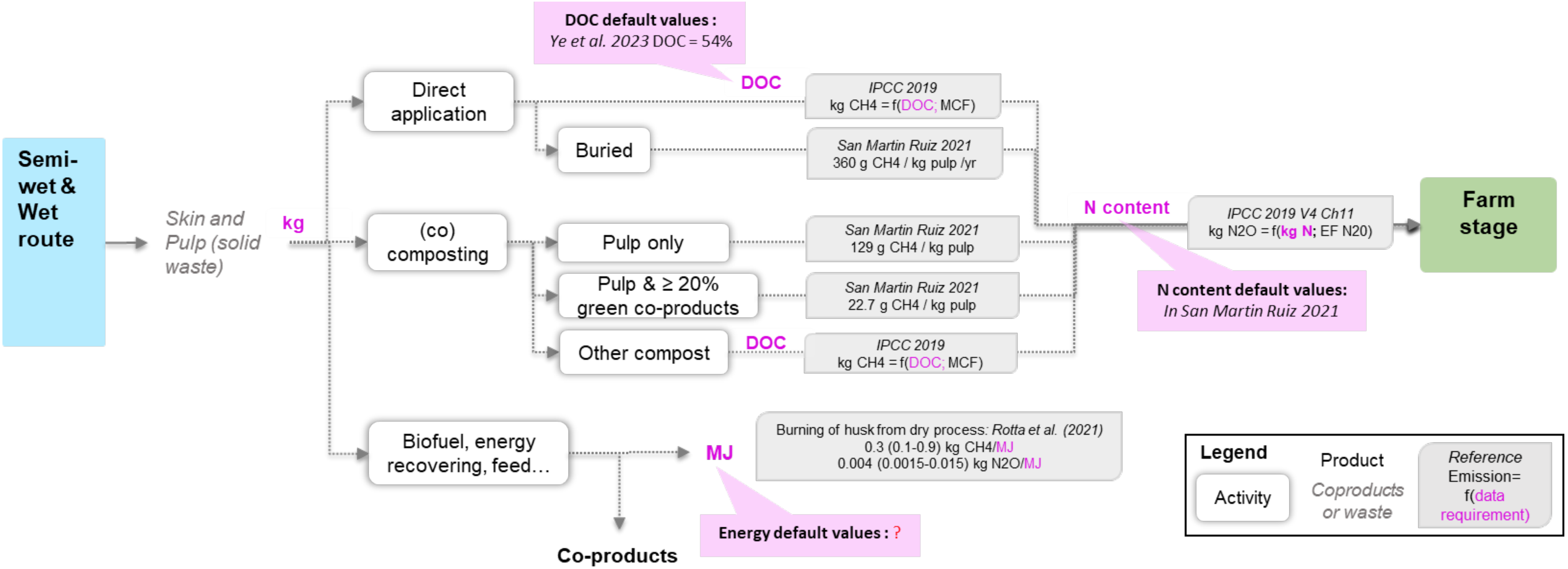

Figure 25. Overview of solid waste possible routes and associated emission factors, reference, data requirement and default values when available

Summary for data requirement:

- Amount of solid waste and composition > Cf. Table 12 from report
- CH_4 emissions from composting:
  1. Use direct CH_4 EF from San Martin Ruiz if this suits your system,
  2. If not, use IPCC 2019 equation using the Degradable Organic Carbon DOC in solid waste from measurements or default 54% value from Ye et al. 2023 and select Methane Correction Factor MCF from table 3.1 in IPCC 2019 V5 Ch3 based on treatment type
- N_2O emissions from application on field: Use IPCC 2019 equation using N content in pulp and compost from San Martin Ruiz 2021 and EF from Table 11.1
- CH_4 and N_2O emissions from burning: based on the amount of energy produced (MJ) Rotta et al. 2021- no MJ default value so far.

Waste water

Recommended approaches are summarized in Figure 26.

METHANE: For CH_4 emissions, use IPCC 2019 V5 Ch6 equation kg CH_4 = f (m3; kg COD/m3)

(> for anaerobic reactor – see below)

kg CH_4 = m3 * kg COD/m3 * EF CH_4

With volume of waste water (m3) based on:

> Specific measurement (strongly recommended due to large variations in practice) NB: We can assume that waste water = water withdrawal.

> Default values from Van Rikxoort et al. (2013, 2014): 36 - 100 m3 /ton green coffee – for a detailed review and other references, see Bessou et al. (under review)

With Chemical Oxygen Demand (COD) based on:

> Specific measurement is strongly recommended because waste water composition varies depending on post-harvest processing techniques, cultivation conditions, coffee fruit maturation degree, harvest method, steps of coffee processing and mechanization (Villa-Montoya et al. 2017)

> Measured COD for various coffee processing waste water type and treatment are available in Chanakya and Alwis 2004 (Table 4) and Villa-Montoya et al. 2017 (Table 2). Values range from 1,5 to 41,7 g/L.

> If none of the above value suits the system studied, use default COD for coffee industry provided in IPCC 2006 (table 6.9) = 9 kg COD /m3 (3 – 15)

With EF CH_4 based on IPCC 2019 V5 Ch6 table 6.8:

> Select EF CH_4 [kg CH_4/kg COD] depending on type of treatment and discharge pathway (examples in figure 2)

The case of anaerobic reactors operating with coffee waste water:

> see specific measurements of methane production, depending on composition (husk, pulp mucilage) and reactor type in: Villa-Montoya et al. 2017 (Table 4)**,** Chala et al. 2018 (Table 7) and Chala et al. 2019 (Table 2).

NITROUS OXIDE: For N_2O emissions, use IPCC 2019 V5 Ch6 equation kg N_2O = f (kg N):

kg N_2O = kg N * EF N_2O * 44/28

With N content based on:

> Specific measurement is recommended

> Measured total N for various coffee processing waste water type and treatment are available in Villa-Montoya et al. 2017 (Table 2)

With EF N_2O based on IPCC 2019 V5 Ch6 table 6.8A:

> Select EF N_2O [kg N_2O-N/kgN] depending on type of treatment and discharge pathway (examples in Figure 26)

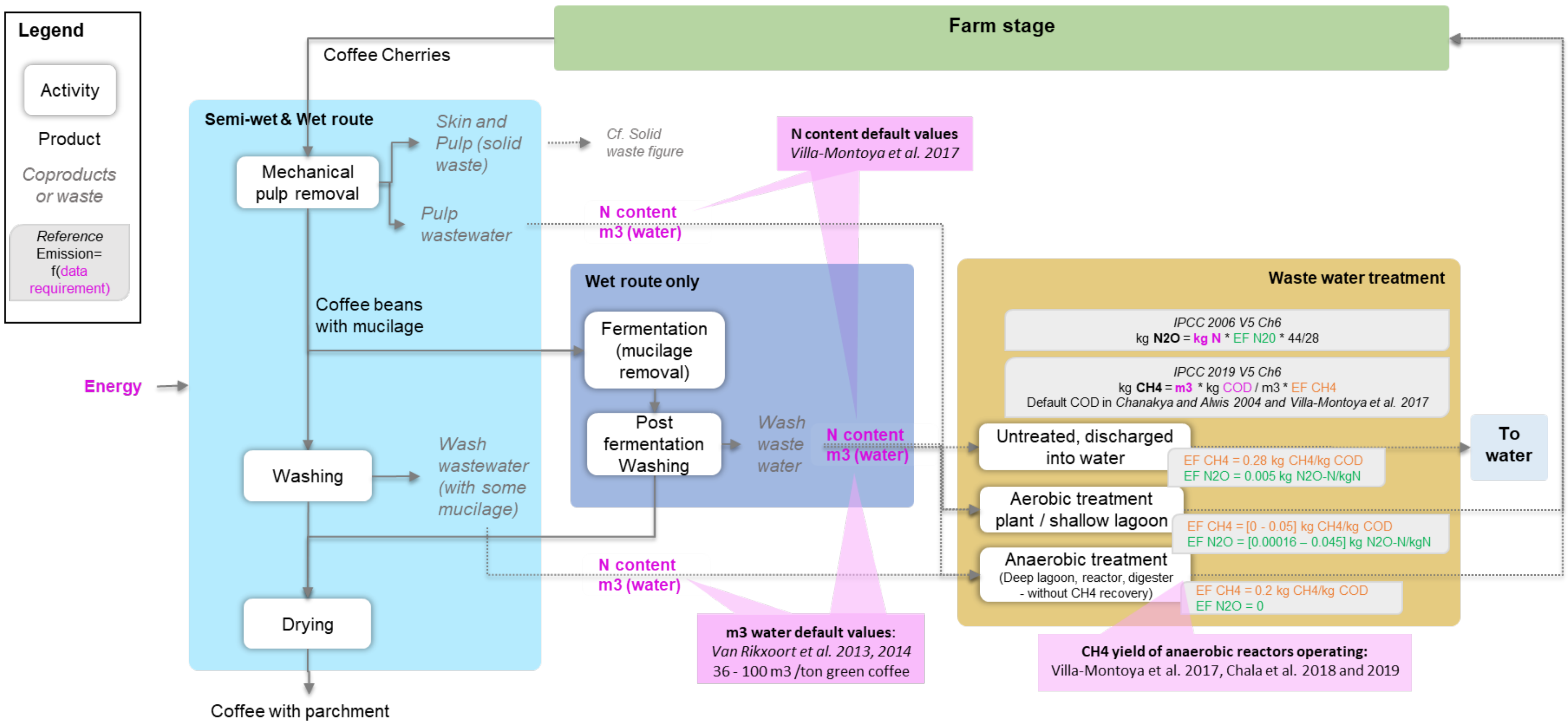

Figure 26. Overview of waste water possible routes and associated emission factors, reference, data requirement and default values when available

Summary for data requirement:

- Energy input
- N_2O emissions:

Volume of waste water, default value in Van Rikxoort et al. 2013, 2014, more details in Bessou et al (under review)

N content of the waste water, measurement recommended or default value in Villa-Montoya et al. 2017

Select N_2O Emission Factor based on IPCC 2019 V5 Ch6 table 6.8A

- CH_4 emissions :

COD of wastewater, measurement strongly recommended or default value in Chanakya and Alwis 2004, Villa-Montoya et al. 2017 and IPCC 2006,

Select Methane Emission Factor from IPCC 2019 V5 Ch6 table 6.8

3.5.2 Characterisation of biochar from and in coffee plantations

There are two dimensions in further investigating and documenting the role of biochar in coffee plantations:

1. Quantifying and characterising the type of biochar that could be produced from coffee plantation residues;
2. Assessing the potential impacts of biochar application in coffee plantations.

Quantifying and characterising the type of biochar

Important biochar characteristics, fur the purpose of its use in agriculture, are pH, electric conductivity and cation exchange capacity. Those variables influence how biochar can be effective in enhancing water retention, retaining nutrients to improve microbial activity, and nitrogen fixing(Mujtaba et al., 2021). A review of chemical properties of coffee residues should be the starting point in identifying biomass sources available for conversion into biochar and their chemical characteristics (Protásio et al., 2013; Vandeponseele et al., 2020).

For the biochar production itself, pilot-scale tests should be implemented on the various potential coffee feedstocks and testing various pyrolysis temperatures and residence times, then quantifying biochar and further outputs. Various technologies can be then applied to further characterise the biochar properties (Jindo et al., 2014; Yaashikaa et al., 2020; Mujtaba et al., 2021).

As mentioned earlier in this report, coffee husk may not be suitable due to too low volume, compared to pruning residues notably, but husk might be used to fuel the biochar production system. There should be a holistic appraisal of the technological optimisation for coffee biochar production accounting for i) minimum viable throughputs ; ii) circular recycling of all potential waste flows within the process and at the coffee value chain level to reduce energy cost; iii) minimising all transport distances and costs.

Quantifying and characterising the impacts of biochar in the coffee plantations

Once biochar feedstock and production process are identified, field experiments are needed to demonstrate the added value of such an input. A first trial should be established with the aim to investigate only one variable regarding biochar (e.g. the type of biochar or the amount applied). The recommended field trial protocol is a Complete Randomised Block Design, within homogeneous pedo-climatic conditions, with at least 3 replicates per treatment, including control (=no biochar input) as one of the treatments. Blocks should be defined on order to minimise the variability within a block (e.g. in terms of planting design, fertilisation) and to maximise the differences across blocks due to undesired factors (e.g. microclimate, hazards). Ideally, this first trial setup should be established in various contrasted pedo-climatic conditions and coffee plantations. The duration of this first trial should be at least 10 years, with first preliminary results analysed after 5 years. Further trials may be established once first results are analysed, in order to test further variables, notably the combination with various types and doses of fertilisers, both mineral and organic.

In the trials, the minimum set of measured variables on an annual basis would be :

- Coffee yields ;
- pH, bulk density (with cylinders), and SOC (dry combustion) over the first 0-20 cm ;
- Biofunctool® indicator sets of soil quality (e.g. POXC, aggregate stability) over the first 0-20 cm (Thoumazeau et al., 2019b; a).

Further measurements should be :

- GHG emissions (CO_2, N_2O, possibly CH_4) with static chambers (at leat 2 measurements per day continuously over 2-3 years) ;

- SOC (dry combustion) over the first 0-100 cm every 5 years.

3.6 Recommendation on the handling of co-products

Table 11 and Table 12 detail possible management pathways for coproducts from green coffee processing. These flows could be handled as a “waste” to be dealt with or as marketable raw materials for other value chains, such as livestock, bioenergy or biorefinery. In principle, and inspired by Circular Economy principles, the concept of cascading should be privileged: to obtain as many and diverse benefits as possible from a “waste” stream (Campbell-Johnston et al. 2020; Jarre et al. 2020). This implies, for the green coffee value chain, to prefer, when possible, co-product handling pathways that enable the recovery of chemicals, nutrients, materials and finally energy.

For the sake of simplicity, we included in “co-products”, all other outputs from the green coffee supply chain, *i.e.* from associated crops to residues or process waste. Ultimately, emissions related to a co-product do not only depend on the nature of a co-product (or type) but on its fate and whether it needs a treatment and can be recycled or not. The management of co-products, hence how to handle their GHG emissions, can vary according to local conditions. Concerning carbon footprint procedures, three cases of management can be considered to appraise various co-products within a given coffee supply chain:

- Waste: Co-products are not used and are dealt with as a waste. In this case, all emissions related to transportation, waste management and disposal must be included.
- Closed-loop valorisation: Co-products are used for another activity inside the system boundaries (*e.g.* application of organic waste such as husk as fertiliser on coffee plantations). In this case, GHG emissions from all steps required from production to valorisation must be included (*e.g.* transportation, composting, field emissions from application, etc.).
- Open-loop valorisation: Co-products are used for an activity outside the coffee system boundaries (*e.g.* associated crop outputs or chemical extraction from coffee residues). In this case, an allocation or system expansion issue arises. Allocation or system expansion procedures were described in section 2.2 according to the ISO and PCR guidelines.

One should notice that co-product handling has been a matter of controversy in the LCA community since the very beginning due to the combined issue of varying interpretation of concepts and guidelines (*e.g.* Heijungs et al. 2021; Dominguez Aldama et al. 2023), and the tremendous influence of the contrasted choices. Co-product handling implies subjective choices and uncertainties that cannot be simply objectified. We hence do not make any further recommendation on those choices but insist on the need for mass balance consistency and co-product handling transparency, as both are guardrails for interpretation and reproducibility of any carbon footprint study. Where co-products may lead to open-loop valorisation, one should carry out some sensitivity analysis on how various choices (allocation ratios and/or system expansion) would affect the final results.

Hence, the key element in any carbon footprint is the construction of a mass balance table that enables the identification of all potential co-products and their management as waste, close- or open-loop co-products. This table should list all carbon partitioning within the system, considering all co-products and their relative humidity. Once the mass balance is established, and all co-products and other mass and energy flows accounted for, a baseline scenario representing the current stable state of the system should be constructed, to be later compared against alternative scenarios on which management changes are introduced.

Table 11 and Table 12 are not exhaustive, as multiple alternative pathways exist. For instance, we retained the most likely storage and composting technologies. Moreover, both tables present a selection of key emission factors. For a complete list of IPCC emission factors please refer to the online IPCC emission factor database (https://www.ipcc-nggip.iges.or.jp/EFDB/) as well as Table 9 and Table 10.

Table 11. Coffee production residual streams, potential substituted products and associated emission factors

Stages	***Waste stream, humidity***	***Potential substituted products***	***Possible uses / treatment***	***Emission factors [1]: CH_4***	***Emission factors [1]: N_2O***	***Emission factors [1]: CO_2***
Plantation stage	Coffee pruning residues, moisture: 3-3.2% FM [3]	Mulching	Left in the soil	N/A or applicable only under special conditions	0.01 (0.001-0.018) kg N_2O-N/kg N	N/A or applicable only under special conditions
			Firewood [4]	0.3 (0.1-0.9) kg CH_4/MJ	0.004 (0.0015-0.015) kg N_2O/MJ [2]	N/A or applicable only under special conditions
Plantation stage	Litter from all plants (coffee and associated ones), 4.7-9.1% FM [3]	Mulching	Left in the soil	N/A or applicable only under special conditions	0.01 (0.001-0.018) kg N_2O-N/kg N	N/A or applicable only under special conditions
Plantation stage	Organic fertilisers (*e.g.* manure) imported into the field	Mineral fertilisers	Storage, solid [5]	5-45 kg CH_4/dairy cattle head*year 3-13 kg CH_4/swine head*year 0.01-0.02 kg CH_4/poultry head*year	0.01 kg N_2O-N/kg N [3]	N/A or applicable only under special conditions
			Composting, passive windrow	N/A or applicable only under special conditions	0.005 kg N_2O-N/kg N [3]	N/A or applicable only under special conditions
			Applied in the soil	Field emissions when applied according to IPCC 2019 Tier 1		
Plantation stage (agroforestry)	Thinning residues (shade and non-shade trees), moisture: 3-3.2% FM [3]	Mulching, fire wood	Left in the soil	N/A or applicable only under special conditions	0.01 (0.001-0.018) kg N_2O-N/kg N	N/A or applicable only under special conditions
			Firewood [4]	0.3 (0.1-0.9) kg CH_4/MJ	0.004 (0.0015-0.015) kg N_2O/MJ [2]	N/A or applicable only under special conditions
			Burned in the field	2.7 g/kg DM combusted	0.07 g/kg DM combusted	1515±177 g/kg DM combusted

Sources and notes: [1] IPCC EFDB (https://www.ipcc-nggip.iges.or.jp/EFDB/), [2] higher heating value of pruning and thinning residues: 19-25 MJ/kg (Mendoza Martinez et al. 2019; Portilho et al. 2020; Kazimierski et al. 2021), [3] Phillis2 database (https://phyllis.nl/), [4] CO_2 emissions from firewood are only accounted for in the case of long-term wooden biomass that would have been previously included in LULUC stocks, [5] only emission factors for solid-base manure storage systems are shown.

Table 12. Green coffee processing residual streams, potential substituted products and associated emission factors

Stages	***Waste stream, mass relative to fresh cherry, humidity***	***Potential substituted products***	***Possible uses / treatment***	***Emission factors: CH_4***	***Emission factors: N_2O***	***Emission factors: CO_2***
Wet processing	Wastewater from mechanical pulp removal → total solids: 3.1 – 30.8 g/l, COD: 1.5 – 25.8 [1] Wastewater from fermentation/washing → total solids: 5.6 – 13.4 g/l, COD: 4.3 – 9.8 [1] Default COD value for the coffee industry wastewater is 9 (3 – 15) kg COD/m^3 effluent [7]	Irrigation water	Direct emission to aquatic environments [5, 7]	MCF = 0.11 (0.004 – 0.27) EF_CH4 = 0.028 kg CH_4/kg COD	EF_effluent = 0.005 (0.0005 – 0.075) kg N_2O/kg N in effluent	N/A or applicable only under special conditions
			Filtering and recirculation of washing/pulping waste water (assuming aerobic treatment) [5, 7]	MCF = 0 (0-0.1) EF_CH4 = 0 kg CH_4/kg COD → Insignificant	EF_plant = 0.016 (0.00016 – 0.045) kg N_2O/kg N in effluent	N/A or applicable only under special conditions
			Ponds/lagoons (assuming reuse in agriculture) [5, 7]	MCF = 0.2-0.8 (0 – 1) EF_CH4 = 0.05 – 0.2 kg CH_4/kg COD	Insignificant	N/A or applicable only under special conditions
			Constructed wetland (assuming reuse in agriculture), subsurface flow type [8]	42 (SD: 20) % of CH_4-C/TOC in influent	0.13 (SD: 0.02) % of N_2O-C/total N in influent	N/A or applicable only under special conditions
			Anaerobic digestion (without methane recovery) [5, 7]	MCF = 0.8 (0.8 – 1.0) EF_CH4 = 0.2 kg CH_4/kg COD	Insignificant	N/A or applicable only under special conditions
	Water vapour lost during fermentation → 21% FM of the cherry [2]	Fraction of boiler energy	Recirculation	N/A or applicable only under special conditions	N/A or applicable only under special conditions	N/A or applicable only under special conditions
Wet processing	Wet residue of pulp from mechanical pulp removal → 29% DM or 45 – 47% FM of the cherry [2, 3]	Organic fertiliser, energy carriers, livestock feed,	Direct application on plantation as fertiliser [9]	Only emissions from application of organic fertiliser	Wet climate: 0.006 (0.001 – 0.011) kg N_2O-N/kg N Dry climate: 0.005 (0 – 0.011 kg N_2O-N/kg N	N/A or applicable only under special conditions

	Mucilage from fermentation/washing → ~5% DM or 12% FM of the cherry [2, 3]	growing substrate	Composting and application on or off farm [6, 9]	MCF = 0.4 – 0.8, depending on aeration	Wet climate: 0.006 (0.001 – 0.011) kg N_2O-N/kg N Dry climate: 0.005 (0 – 0.011 kg N_2O-N/kg N	N/A or applicable only under special conditions
			Livestock feed, biofuel, energy recovery, growing mushrooms, production of citric acid and natural aromas, gasification, ethanol production (pre-treatment needed in most cases)	N/A or applicable only under special conditions	N/A or applicable only under special conditions	N/A or applicable only under special conditions
Wet processing	Parchment → 5.6 – 5.8% DM of the cherry [2, 3]	Energy carriers, livestock feed, growing substrate	Biofuel, energy recovery, gasification, livestock feed, growing mushrooms, producing a moulded article from coffee bean hulls	N/A or applicable only under special conditions	N/A or applicable only under special conditions	N/A or applicable only under special conditions
Dry processing	Husk (pulp + mucilage) → ~45% DM of the cherry [3]	Biorefinery feedstock, organic fertiliser	Production of citric acid Extraction of natural aroma compounds	N/A or applicable only under special conditions	N/A or applicable only under special conditions	N/A or applicable only under special conditions
			Composting and application on or off farm [6, 9]	MCF = 0.4 – 0.8, depending on aeration	Wet climate: 0.006 (0.001 – 0.011) kg N_2O-N/kg N Dry climate: 0.005 (0 – 0.011 kg N_2O-N/kg N	N/A or applicable only under special conditions
			Burning [10]	0.3 (0.1 – 0.9) kg CH_4/MJ	0.004 (0.0015 – 0.015) kg N_2O/MJ	N/A or applicable only under special conditions
Semi-washed (semi-wet) processing	Sticky husk (pulp + mucilage) → ~43% FM of the cherry [4]	Livestock feed, organic fertiliser	Direct application on plantation as fertiliser [9]	Only emissions from application of organic fertiliser	Wet climate: 0.006 (0.001 – 0.011) kg N_2O-N/kg N Dry climate: 0.005 (0 – 0.011 kg N_2O-N/kg N	N/A or applicable only under special conditions

			Composting and application on or off farm [6, 9]	MCF = 0.4 – 0.8, depending on aeration	Wet climate: 0.006 (0.001 – 0.011) kg N_2O-N/kg N Dry climate: 0.005 (0 – 0.011 kg N_2O-N/kg N	N/A or applicable only under special conditions
			Livestock feed, biofuel, energy recovery, growing mushrooms, production of citric acid and natural aromas, gasification, ethanol production (pre-treatment needed in most cases)	N/A or applicable only under special conditions	N/A or applicable only under special conditions	N/A or applicable only under special conditions

Sources and notes: [1] Chanakya and De Alwis (2004), [2] Rotta et al. (2021), which seems more up to date that the recommendation of assuming “576 kg cherry pulp/tonne green coffee beans; 70% water in coffee cherries” in EPD (2019), [3] del Castillo et al. (2019), [4] Karim et al. (2019), [5] When the maximum CH_4 producing capacity of an industrial wastewater (EF_CH4) is unknown, the maximum CH_4 producing capacity for domestic wastewater (0.25 kg CH_4/kg COD) should be used → CH_4 emissions are computed as EF_CH4 * methane correction factor (MCF), [6] IPCC 2019 V5 Ch3 Eq3.2: CH_4 emissions are computed as a proportion of Degradable Organic Carbon (DOC) in the residue that can decompose (DOCf = 0.7 for highly decomposable waste, Table 3.0) * MCF (Table 3.1) * DOC (DOC = 36% for food industries sludge, IPCC 2019 V5 Ch2 Table 2.4a), [7] IPCC 2019 V5 Ch6 Tables 6.8, 6.8a and IPCC 2006 V5 Ch6 Table 6.9, [8] 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands Table 6.2, including factors corresponding to other types of constructed wetland, [9] IPCC 2019 V4 Ch11 Table 11.1, [10] IPCC 2006 V2 Ch2 Table 2.4 (proxies for coffee residues: other primary solid biomass or biomass fraction of MSW)

3.7 Recommendation on the interpretation and diffusion of results

Below is a checklist of all mandatory information in a carbon footprint study report (ISO 14067:2006), plus a few additional recommendations: (note that there are other requirements when a communication (public or not) is intended - Table 13)

Table 13. Checklist of information required in a CFP report.

Assessment steps	***Mandatory and optional (ISO 14067)***	***Additional recommendations***
Goal and scope	Functional Unit (as precise and specific as possible) and reference flow Scope with justifications and exclusions System boundary Cut-off criteria Selected allocation approach Disclosure and justification of value choices Time period for which the CFP is representative	A diagram to visualise processes and co-products/wastes included in the system boundary A diagram to present the various phases of the perennial cycle length and their lengths
LCI	Description of the stages of the life cycle Description of significant unit processes description of data Time period related information	Description of primary and secondary data Data Quality Rating scores Highlight main sources of uncertainty Description of the system typology and sampling Provide all emission factors used Make sure all flows are balanced
LCIA		The source and date of the GWP factors used
Results – GHG values	To be documented separately - GHG emissions and removals: • linked to the main life cycle stages, including the absolute and the relative contribution of each life cycle stage • arising from fossil carbon sources and sinks • arising from biogenic carbon sources and sinks (unless included in product) • resulting from LUC • soil carbon change (if calculated) Graphical representations If product comparison: compliance with Annex D in ISO 14067	Present results in accordance with the system boundary and the FU (specifying the detailed FU together with the results) Recall allocation and LUC assumptions when presenting the results In the case of LULUC, provide results with and without LULUC specifying the assumed date of LULUC and the time period accounted for to identify and allocate impacts Provides detailed absolute values (kg CO_{2eq}) and contribution analysis charts Avoid using radar charts, prefer diagrams
Interpretation	Assessment of data quality (*e.g.* sensitivity analysis and uncertainty assessments) Sensitivity check regarding the significant inputs Results of the life cycle interpretation, including conclusions and limitations	Clearly identify “baseline scenario” results vs. “scenario analysis” results

4 Conclusions

To reveal the state-of-the-art of green coffee carbon footprint, we first carried out a narrative literature review of 34 studies. Across those studies, the median carbon footprint was 3.6 $kgCO_{2eq}$/kg green coffee (min: 0.15 $kgCO_{2eq}$/kg green coffee; max: 14.5 $kgCO_{2eq}$/kg green coffee). Unsurprisingly, N-fertilisers were the main common contributors, besides land use change, with some cropping systems penalised through too low or too high fertiliser inputs. But differences across studies were mostly driven by discrepancies in the methodologies and data used, which overwhelmed the potential intrinsic effect of contrasted production systems. Main inconsistencies concerned the modelling of the perennial crop, the biomass accounting, including LULUC, and the handling of co-products (including residues and processing waste). We further investigated these aspects in order to provide sound and practical recommendations based on the state-of-the-art.

The reviewed guidelines included baseline LCA and Carbon footprint ISO standards, as well as Product Category Rules specific to coffee. Guidelines all agree on the fundamental principles and main recommendations but are sometimes not precise enough, especially when choices arise that cannot be strictly objective, *e.g.* when dealing with system multifunctionality or time integration. We recommend to apply ISO 14067 and Coffee PCR as far as possible and to consider Cirad recommendations to further increase the robustness and thoroughness of the assessment. We particularly emphasise on the consistency of the perennial cycle and the LULUC modelling. Such modelling challenges raise recurrent issues in life-cycle based assessment for agricultural systems given the difficulty to integrate the time dimension in an assessment snapshot, although time is quite critical for living systems. Nevertheless, when properly considering and displaying assumptions made on the time dimension, including how it affects carbon biogenic inclusion or not, consistent and reproducible assessments are made possible. We completed the methodological recommendations with in-depth scientific reviews on knowledge and data available for quantifying biomass increment and stocks as well as emissions to the environment all along the green coffee supply chains.

In any life-cycle based assessment, the transparency on the exact system boundaries and all embedded assumptions is a key principle. Life-cycles are complex and sometimes impossible to fully grasp; their modelling require simplification and choices. All choices embedded in the goal and scope of a study may have a critical impact on the results. One may always bear in mind that LCA or carbon footprint results remain potential impacts (no absolute or true results) that intrinsically depend on the study design, *i.e.* how the studied system is simplified, the reliability and precision of data used, and the known and unknown involved mechanisms. Therefore, the results are not as important as what can be learnt from testing their robustness and how they change depending on methodological choices as well as on the data quality. Those results must be used as monitoring tools and be regularly updated as soon as more knowledge or better data is available.

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ANNEX 1: METHOD FOR CALCULATING TIME-AVERAGED CARBON STOCKS OF A LAND-USE SYSTEM ACCORDING TO THE METHOD DESCRIBED BY VAN NOORDWIJK (ICRAF, 1996)

Time-averaged carbon for the different land-use systems at the ASB sites was calculated as follows: 1) calculation of the C accumulation rates (^{Ic}) for each land-use system based on the carbon stock and the average age of each system sampled, and 2) calculation of time- averaged C stocks for the duration (rotation time) of each land-use system based on the C accumulation rates and duration of each of the phases in that particular land-use system.

Carbon accumulation rates (I_c , t C ha^{-1} yr^{-1}) for fallow regrowth were determined according to the method described by van Noordwijk (ICRAF, 1996) where the average C stock value of the fallows sampled (C_s) was divided by the average age (T_s) of the plots sampled. It is assumed that the carbon increase rates (I_c) are linear throughout the time period of fallow regrowth (T_f). The carbon stored in fallows (C_m) of specific ages (T_f) can then be determined as: $C_m = I_c * T_f$. The time-averaged C stock for a crop-fallow system that has little time in the cropping phase and negligible C stored over that time is essentially the C stored in the fallow vegetation at the time of reclearing (C_m) divided by 2 or the C accumulation rate (I_c) time the number of years of fallow (T_r) divided by 2.

For tree crop plantations, however, the carbon accumulation rates may not be linear throughout the entire rotation age of the system. The system may reach a maximum carbon stock (C_{max}) at a time (T_{max}) before the end of the rotation (T_r). As an example, a coffee plantation may reach the maximum carbon stock in 7 years but production continues for an additional 5 years, giving a rotation time (T_r) of 12 years, at which time the plantation is cut and re-established. In such cases the C accumulation rate (I_c) is determined by dividing C_{max} by T_{max}. This can only be determined if plantations that have reached maximum biomass have been sampled, and the age at which maximum biomass attained is known. For such systems, the time-averaged C stock for a land-use system is determined as the weighted average of the C stocks for the different phases of the rotation.

Calculation of the time-averaged carbon stock of the coffee plantation described above, with an establishment phase of 7 years to reach maximum biomass followed by 5 years of production before cutting and re-establishment will serve as an example. The values of $I_c = 2.2$ t C ha^{-1} y^{-1} and $T_{max} = 7$ were established from field data. The time- averaged C (C_{ta1}) for the establishment phase is equal to: $(I_c*T_{max})/2$ or 7.7 t C ha^{-1} for the 7 years. The time-averaged C for the remaining production phase (C_{ta2}) of 5 years is simply equal to C_{max} or 15.4 t C ha^{-1}. The time-averaged C for the entire system rotation ($LUSC_{ta}$) is the weighted average for the two phases:

$$[C_{ta1} * T_{max}] + [C_{ta2} * (T_r - T_{max})] / T_r = [53.9+77]/12 = 10.9 \text{ t C ha}^{-1}].$$

It is possible to compare the time-averaged C stocks of the different land-use systems within a site to that of the forest as a simple fraction or percentage of the forest biomass. To make cross-site comparisons of the systems it is necessary to include the original forest biomass at each site.

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