Measuring and Mitigating GHGs: Coffee

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There are millions of farms globally, each using a unique set of practices to cultivate their products in the local climate and soil. Thus, for any commodity, there are many thousands of different production systems and many thousands of different sources of greenhouse gases (GHGs). The relative GHG emissions of producing the same product may differ drastically depending on how and where it is grown. To fully understand how to mitigate emissions and on which farms to focus mitigation efforts, we need a better grasp of the variations and gaps in data.

The authors do not think all the information to quantify GHG emissions from the coffee value chain exists – at the very least, not in one place. This document is our attempt to collate currently available information. This is a working draft; debate, discussion, and comments are welcomed to advance the understanding of this topic. WWF will be producing similar pieces on other key food commodities to stimulate similar discussions. All comments should be justified with evidence and data and sent to Emily Moberg at GHGCommodities@wwfus.org.

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ABOUT COFFEE

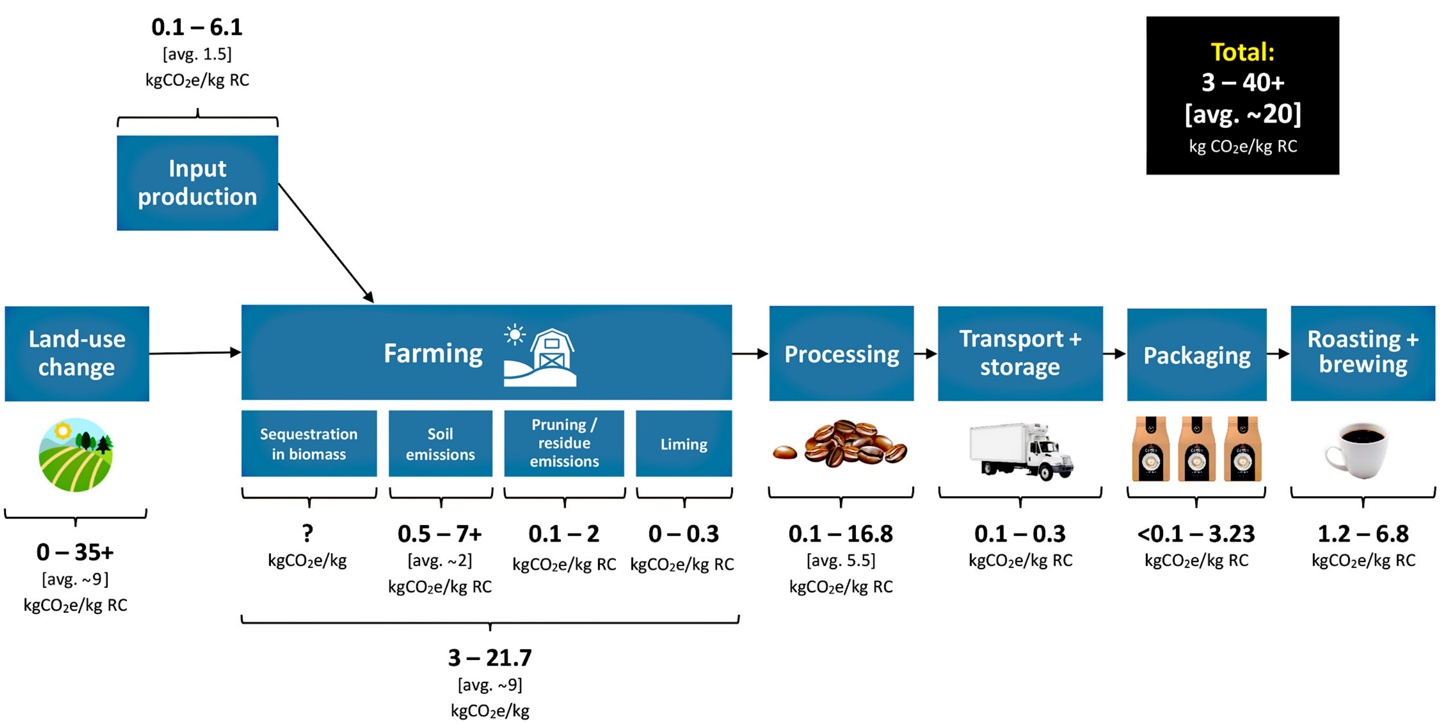
Coffee is the world's most widely traded tropical agricultural commodity, valuing approximately U.S. $16.5 billion/yr in recent years[1] and providing a major source of revenue for more than 40 tropical countries. Most coffee is produced by smallholders, many of whom struggle to earn their livelihood from coffee production.

COFFEE SUPPLY CHAINS

The coffee value chain begins with producers, primarily smallholder farmers; these farmers produce coffee cherries, which are then processed via wet or dry methods to yield green coffee, or unroasted beans. Next, many of these coffee beans are exported to the destination country for roasting, distribution, and consumption. The finished product is then sold to retailers and distributors, where it is either brewed directly or sold to consumers who brew it at home.

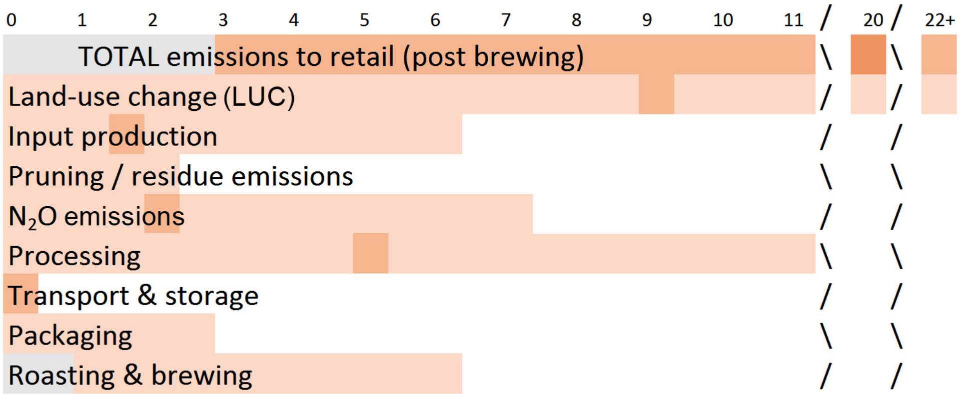
GHG EMISSIONS FROM COFFEE SUPPLY CHAINS

Figure 1: Range of GHG emissions from coffee supply chains



Estimates of GHG emissions from coffee range from about 3 to more than 40 kgCO_2e/kg roast coffee (RC). Average emissions are likely about **20 kgCO_2e/kg RC**, driven largely by significant land-use change (LUC), fertilizer use, and wet-processing effluent, which are each potentially large GHG contributors.

The full range of impacts (in kgCO_2e/kg RC) is shown on the following page, with the typical range highlighted in darker orange.



The full range of impacts (in $kgCO_2e/kg$ RC) is shown above, with the typical range highlighted in darker orange.

LUC

When habitats (typically forests) are cleared for coffee farming, the carbon stored in the trees is quickly released as CO_2. While not all coffee farms are built on recently cleared forest, when this LUC occurs, the GHG emissions are significant; they can reach up to 35 $kgCO_2e/kg$ RC even when these emissions are spread out across many years.[2]

Despite widespread agreement that coffee farming is an ongoing, major source of deforestation, it is typically excluded from life cycle-based estimates of carbon footprints for coffee.

- World Resources Institute (WRI) Global Forest Watch estimates about 0.13 million hectares have been lost each year to coffee cultivation over the last twenty years. This equates to approximately **45 million tCO_2e/yr**, or **6.6 $kgCO_2e/kg$ RC** globally.[3]
- Poore and Nemecek's analysis has a weighted average of **6.5 $kgCO_2e/kg$ RC** with another **2.5 $kgCO_2e/kg$ RC from burning for land clearing**. This amounts to **55–76 million tCO_2e/yr**.
- Usva's 2020 study using the Blonk LUC methodology found LUC emissions ranging from **3.7 to 17.9 $kgCO_2e/kg$ RC** for some subnational Latin American regions.

LUC typically contributes nearly half of a cup of coffee's GHG footprint at 9 $kgCO_2e/kg$ RC. However, this footprint can be 0 or over 35 $kgCO_2e/kg$ RC, depending on a particular location's land-use history.

Farming and Harvesting

Farming and harvesting contribute between 0.9 and 8 $kgCO_2e/kg$ RC. The main contributors to on-farm emissions are embedded emissions in fertilizer and nitrous oxide (N_2O) emissions from fertilizer and residue.

- **Fertilizer:** The production of synthetic fertilizers is a GHG-intensive process. Embedded emissions in inputs averaged **0.6 $kgCO_2e/kg$ RC** (range: 0.2 – 6.1).[4]
- **N_2O emissions:** Fertilizer application and crop residues also cause N_2O, a potent GHG, to be emitted. These emissions range from **0.58 to 7+ $kgCO_2e/kg$ RC (avg. ~ 2)**;[5] higher-end estimates tend to be from higher fertilizer application rates, which did produce higher yields. Crop residues contribute between 0.1 and 2 $kgCO_2e/kg$ RC to this total.[6] Organic and traditional polyculture farms often have heavy tree canopies and, consequently, greater crop residue emissions.[7]
- **On-farm carbon stocks:** There have been many studies on the differences in on-farm carbon stocks between full-sun monoculture and differing levels of shade. It is uncontroversial that plantations with many trees have significantly higher carbon stocks (~20 – 60 tC/ha vs. 1 – 9 tC/ha);[8] the total effect on coffee yields (and whether other products like timber or bananas are produced) is less clear. Some studies argue intermediate shade produces the highest yields;[9] others that agroforestry and full-sun yields are similar;[10] many others that full-sun yields are significantly higher.[11] The focus is typically on aboveground biomass, although some studies also include belowground biomass and litter – both of which are significant pools in polyculture coffee systems; soil carbon is typically not considered.[12] Establishing the contribution of on-farm carbon stocks per unit of coffee, on average, is not feasible at this stage.

Emissions on farms are highly variable but arise largely from fertilizer application and organic residues. They can range from 0.9 to 8 $kgCO_2e/kg$ RC.

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Coffee Processing (cherries to green coffee)

Coffee processing includes the conversion of coffee cherries produced on the farm into the raw green coffee beans ready for roasting. Emissions from processing range from 0.3 to up to 14.7, with an average of **5.5 $kgCO_2e/kg$ RC**.[13]

There are two main processing methods: wet and dry processing. The wet process consists of three subprocesses: pulping, fermentation/demucilaging, and drying (naturally or artificially). The dry method consists of either natural (sun) or artificial drying, which results in emissions from electricity use. Wet processing is significantly more complicated and uses a large amount of water, which then contains organic matter that can decompose. These processing methods may have significant effects on the quality and flavor of the coffee.

Many studies explicitly exclude the decomposition from wet processing, despite the fact that it may add between 0.9 and 16.8 $kgCO_2e/kg$ RC;[14] typical values based on wastewater contents are likely on the lower end.[15] When this effluent is used as fertilizer or methane captured as biogas, these emissions may be avoided, although there is no data on how frequent these practices are.

Emissions from coffee processing are also highly variable depending on the method used. Dry processing typically produces lower emissions than wet processing, which also has emissions from organic matter decomposition Typical emissions from processing are over 5 $kgCO_2e/kg$ RC.

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Post-processing (green coffee to cup)

After green coffee is produced, it is typically shipped to the country of consumption; emissions from transport are typically small relative to on-farm, processing, and brewing emissions. Retail packaging is a small contributor to overall emissions except for home-brewing packaging, which can be ~0.85 – 3.23 kgCO_2e/kg RC, with the high-end intensities arising from single-use pods.[16]

Brewing coffee is also responsible for emissions because of the energy required to heat the water (and, in some cases, keep it warm). Thus, how coffee is brewed dramatically influences emissions: French presses/drip filters emit 1 kgCO_2e/kg RC, while automatic coffee machines emit between 2.5 and 6 kgCO_2e/kg due largely to high levels of electricity used to keep the water warm.[17]

Packaging can significantly add to emissions (0.85 – 3.23 kgCO_2e/kg RC), especially for single-use pods.

The brewing process uses electricity; higher emissions result from operations where water is kept warm for long periods.

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OUTLIER EMISSIONS SOURCES

The variability in emissions per kg RC highlights the large mitigation potential that exists across current practices. Here we highlight the "low hanging fruit," or practices that drive unusually high emissions intensity. These practices may be good targets for initial screening for improvement.

- **Prevent deforestation:** The footprint from deforestation is large, and deforestation of forests for coffee continues. As climatic conditions threaten coffee production, the pressure on natural forests will likely increase.

- **Treat wet processing effluent:** The degradation of organic effluent from wet processing may produce significant GHG emissions and nutrient pollution. This material can be beneficially used for fertilizer or, potentially, biogas.
- **Minimize single-use packaging:** Single-use packaging for coffee greatly increases its footprint and likely contributes to material waste pollution.
- **Avoid "always on" coffee makers:** Coffee shop and at-work coffee machines are often on overnight or over long periods of time to keep water warm. This uses a large amount of electricity that is not necessary.

PRODUCTION SYSTEMS

There are two major types of coffee: arabica and robusta. These coffees are produced in tropical areas across the world using very different methods for cultivation and processing. These different production systems influence both yields and the amount of carbon on-farm.

Arabica: Arabica coffee is the one most commonly produced (about 70% of global total) and it is worth more. Arabica coffee requires cooler temperatures for production, and yields per hectare are often lower than those of robusta. Most studies of GHG emissions from coffee use data for arabica.

Robusta: While robusta coffee is a commonly produced and traded type of coffee, studies on the GHG emissions from its production are few, so we cannot currently comment on how GHG emissions differ from those from arabica production.

Monoculture: Monocultures grow only coffee and are economically very efficient. Monocultures may, however, be susceptible to certain pest and disease outbreaks. Monocultures are typically classified as shaded or unshaded. Full-sun monocultures have very low carbon stocks on-farm.

Polyculture: Polyculture production incorporates two or more plants within one agricultural system; these other plants (often bananas or timber) also produce economically valuable products. Shaded polyculture can be divided into two categories: commercial and traditional. Traditional polyculture has higher carbon stocks than commercial polyculture (about 50%) due to large, old native plants, while both polyculture systems have significantly (3x – 4x) higher stocks than monoculture systems.[18]

Between monoculture and polyculture, the differences in carbon stocks and coffee yields likely drive the overall footprint; however, the evidence is currently sparse and unsettled. There are also likely differences between smaller and larger coffee operations, which are not well characterized in the literature.


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REGIONS

Coffee is produced only in tropical regions. Variation in emissions across geographies is driven largely by historical deforestation and yields.

Information on the total production of green coffee, percentage of that coffee exported, range of GHG intensity per kg RC, the yield of green coffee per hectare, and percentage of arabica production are listed for a few major coffee-producing countries. (Together, these five countries produced 73% of the world's coffee over the past five years.)[19]

Table 1: Characteristics of selected coffee producing countries

	Production (million tonnes/yr)[20]	Export (%)[21]	Yield (tonnes green coffee/ha)[22]	Forest loss from coffee (1000 ha/yr)[23]	% Arabica[24]	GHG intensity ($kgCO_2e$/kg RC)
Colombia	848	87	1	4.2	100	9.8 – 30
Ethiopia	437	55	0.65	1.9	100	?
Vietnam	1,760	85	2.6	9.7	4	~6.5
Brazil	3,661	56	1.6	30.4	74	5 – 7
Indonesia	636	60	0.56	27.8	11	? – 50+

While data on the GHG footprint per country are limited, we do know that emissions from forest loss are significant in many of these countries. Conservatively, LUC emissions average, in $kgCO_2e$/kg RC, Colombia 2.7, Ethiopia 2.6, Vietnam 3.6, Brazil 4.7, and Indonesia 22.

MITIGATION

The wide range of emissions from different stages and processes within coffee production suggests that significant scope for better production already exists. A key first step is to ensure that additional forest and habitat are not converted to coffee growing, as the GHG impact of these conversions is large and takes decades to recover. Table 2 (pg #12) outlines additional intervention strategies and methods to reduce heavy emission sources. Note that tailoring and scaling these interventions are made particularly challenging by the high proportion of smallholder production. For producers of specialty coffees, incentives like premiums, financing, or long-term contracts may be sufficient to spur change; the monetary benefit of carbon credits alone is unlikely to produce farmer-level action.

Prevent further deforestation: Preventing further deforestation is the highest-impact action that can be taken. As coffee production is dominated by


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smallholders[25] and climate change threatens the viability of farms, steps to ensure profitability and resilience to extreme events will be critical to curbing further expansion.

Expand production onto degraded lands: There is limited research identifying where coffee expansion could sustainably occur at any scale. For other commodities, expanding into degraded lands can even sequester carbon; agroforestry coffee could potentially do this as well, but research into the feasibility is needed.

Promote agroforestry: Planting nitrogen-fixing crops and/or shade trees intermingled with coffee has the potential to sequester additional carbon on an areal basis. However, in some cases, coffee yields from agroforestry may be reduced, which could actually increase the footprint per unit of coffee (and could lead to further conversion to meet demand). As agroforestry can also involve diversifying coffee crops with crops or trees, providing additional income potential, its economic effect can be positive. Allocation of sequestered carbon across these multiple products is also understudied.

Agroforestry may also provide resilience against disease and extreme weather events, although the quantitative effects are not well characterized. This deserves much more attention, given the importance of coffee cultivation for livelihoods.

Improve fertilizer use: Balanced fertilizer use is critical for agriculture; when the application is too low, small yields result; when fertilizer use is too high, the emissions embedded in the production and from nitrification are wasted. The use of organic wastes from coffee processing for fertilizer can reduce the emissions from input production and minimize methane emissions from wastewater decomposition.

Greater farm-level analysis of soil needs, as well as training on both the appropriate type and amount of fertilizer to be used, can reduce emissions while holding the potential to increase yields. However, such interventions can be intensive, requiring soil testing and education across many small farms. Where possible, partnering with co-operatives, which are prevalent throughout Latin America in particular though also present in other regions, would enable companies to work with trusted local partners that have strong relationships with growers already. The potential for fertilizer-based interventions to mitigate emissions will vary considerably depending on how fertilizer is already used in a given region, but it has the added benefit of additional ecosystem services by its potential to improve soil health, yields, and water quality.

Table 2: Possible interventions and improved management practices that contribute to a reduction in GHG emissions and represent a value proposition to the coffee industry.

Mitigation Potential Table				
Intervention	Target	Cost	Mitigation Potential	Barriers
Prevent deforestation	Governments	\$10–\$100/tCO_2e/yr[26]	0.05–0.08 $GtCO_2e$/yr (based on current deforestation rates for coffee)	
Plant nitrogen-fixing crops or shade trees; agroforestry	Farms	?	~0.8 $GtCO_2e$ (total, assuming 40tC/ha additional with agroforestry; uptake on 50% of all coffee lands with no loss in yields)	Yields from agroforestry may be lower, although evidence is mixed
Improve fertilizer use	Farms	?	?	Requires local tailoring and technical expertise
Use waste organic matter as fertilizer	Farms and mills	?	>0.001 Gt/yr (if all fertilizer inputs could be replaced, assuming 1.5 $kgCO_2e$/kg RC)	

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TOOLS & DATA AVAILABILITY

The GHG footprint of coffee is not well characterized in the literature, and many key production practices are not well quantified, especially for on-farm operations. Like with other tree crops, there are few tools available for characterizing on-farm emissions, save for the generic "tree crop" category. Based on interviews, these on-farm tools are not widely used.

- **Cool Farm Tool:** An online tool produced by the Cool Farm Alliance that allows farmers to specify fertilizer use and cultivation practices to calculate a GHG footprint. While oil palm is not a specific crop, tree crops, in general, can be modeled using this tool. The footprints are not regionally tailored, but the tool works globally.

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CITATIONS/FOOTNOTES

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11 E.g., Capa, Pérez-Esteban, and Masaguer, "Unsustainability of Recommended Fertilization Rates for Coffee Monoculture Due to High N_2O Emissions"; Pinoargote et al., "Carbon Stocks, Net Cash Flow and Family Benefits from Four Small Coffee Plantation Types in Nicaragua." No reference.

12 However, in studies that do include it, there were not significant differences across plantation types, e.g., Susan Balaba Tumwebaze and Patrick Byakagaba, "Soil Organic Carbon Stocks under Coffee Agroforestry Systems and Coffee Monoculture in Uganda," *Agriculture, Ecosystems & Environment* 216 (2016): 188–93; Ehrenbergerova et al., "Carbon Stock in Agroforestry Coffee Plantations with Different Shade Trees in Villa Rica, Peru."

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16 Poore and Nemecek, "Reducing Food's Environmental Impacts through Producers and Consumers"; Sybille Büsser and Niels Jungbluth, "The Role of Flexible Packaging in the Life Cycle of Coffee and Butter," *The International Journal of Life Cycle Assessment* 14, no. 1 (May 1, 2009): 80–91, https://doi.org/10.1007/s11367-008-0056-2.

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20 USDA Production, Supply, and Distribution data for 2016–2021.

21 USDA Production, Supply, and Distribution data for 2016–2021.

22 Data from FAOSTAT, average 2014–2019 (most recent years available).

23 Data from WRI's analysis of commodity-driven forest loss disaggregated by country from 2001–2015.

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