Supplementary information

# Evaluating Global Species Loss from Coffee Production in Agroforestry and Conventional Systems Using Life cycle Assessment (LCA)

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## 1. The CFs used in this study for the different impact categories

**Table S1** The CFs used in this study for the different impact categories. TE refers to terrestrial ecosystems, FE to freshwater ecosystems and ME to marine ecosystems. Note that the spatial detail for the selection of CFs is specific to the calculation of coffee cultivation impacts, whereas the upstream processes sourced from ecoinvent may have less precise spatial detail

| Impact category | CF | Ecosystem | Additional information |
|---|---|---|---|
| Land stress (occupation)* | Marginal, ecoregion NT0109, taxonomically aggregated | TE | |
| Land stress (transformation)* | Marginal, ecoregion NT0109, taxonomically aggregated | TE | Included only in the sensitivity analysis |

| | | | |
|---|---|---|---|
| Climate change** | Mix marginal/average, 100 a, all impacts, global resolution | TE | |
| Climate change** | Mix marginal/average, 100 a, all impacts, global resolution | FE | |
| Acidification** | Marginal, 2.0° x 2.5° resolution | TE | |
| Freshwater eutrophication** | Linear, Magdalena-Sinu (FEOW 2019) | FE | |
| Marine eutrophication** | Linear, Magdalena basin (Verones 2021) | ME | |
| Water stress** | Marginal, all impacts, 0.05° x 0.05° resolution | FE | |
| Terrestrial ecotoxicity** | Linear, 100 a, global resolution | TE | Included only in the sensitivity analysis |
| Freshwater ecotoxicity** | Linear, 100 a, global resolution | FE | Included only in the sensitivity analysis |
| Marine ecotoxicity** | Linear, 100 a, global resolution | ME | Included only in the sensitivity analysis |

*GLAM method (Scherer et al. 2023a; Scherer et al. 2023b)

**LC-IMPACT method (Verones et al. 2020a; Verones et al. 2020b; Verones 2021)

## 2. Upstream processes from ecoinvent v3.10 used in the LCA model

**Table S2** Upstream processes from ecoinvent v3.10 used in the LCA model

| Product | Process in ecoinvent v3.10 |
|---|---|
| **Fuel** | |

| | |
|---|---|
| Diesel production | Diesel {CO}\| market for diesel \| Cut-off, U |
| **Fertilizers** | |
| Nitrogen fertilizer production | Inorganic nitrogen fertiliser, as N {CO}\| market for inorganic nitrogen fertiliser, as N \| Cut-off, U |
| Phosphorous fertilizer production | Inorganic phosphorus fertiliser, as P2O5 {CO}\| market for inorganic phosphorus fertiliser, as P2O5 \| Cut-off, U |
| Potassium fertilizer production | Inorganic potassium fertiliser, as K2O {CO}\| market for inorganic potassium fertiliser, as K2O \| Cut-off, U |
| **Soil acidity correctives** | |
| CaCO3 production | Calcium carbonate, precipitated {RoW}\| market for calcium carbonate, precipitated \| Cut-off, U |
| **Energy** | |
| Electricity production | Electricity, low voltage {CO}\| market for electricity, low voltage \| Cut-off, U |

## 3. Sensitivity analysis calculations

### 3.1. Calculation of land transformation

The estimated land transformation impacts in sensitivity analysis 3 were based on the average land transformation related to coffee cultivation in Colombia in the past 20 years. The average coffee cultivation related land transformation in Colombia during 2001-2020 was 12 746.2 ha and the total land area used for coffee production in Colombia in 2020 was 844 744 ha (FAOSTAT 2024a; FAOSTAT 2024b; Järviö et al. submitted). 1 kg of parchment coffee (the FU of this study) corresponds to 0.8 kg of green coffee (ITC 2021). Thus, the land transformation caused by the cultivation of 1 kg of parchment coffee was calculated by dividing the total coffee cultivation related land transformation in Colombia in 2020 by the total land area used for coffee cultivation in Colombia in 2020, the yields of coffee per ha, and green coffee rate (0.8). Land transformation was assumed to be from "managed forest, minimal" to "plantation, light" (conventional coffee) and "plantation, minimal" (coffee agroforestry) (Scherer et al. 2023). The forest transformed to plantation could also be a natural rainforest or even "managed forest, light" where e.g. selective logging can be practiced according to Scherer et al. (2023). We assumed "managed forest, minimal" as an average of these where minor human-caused disturbances occur, such as trail or path (Scherer et al. 2023).

### 3.2. Calculation of the level of $CH_4$ emissions from composting

The sensitivity analysis 4 was done for the level of methane emissions from composting. In the literature there was a lot of variation in composting methane ($CH_4$) emission factors. In this study the default factor of IPCC (2006) Tier 1 method of 4 g $CH_4$ $kg^{-1}$ waste treated was applied. We could not find an emission factor for composting a combination of 80 % coffee pulp and 20 % poultry manure. However, a study by San Martin Ruiz et al. (2021) measured the methane emissions from coffee by-product composting with different shares of coffee pulp and green waste (weeds, plant clippings and structural materials) in the input. The $CH_4$ emissions from composting coffee pulp alone without any green waste in the input had the highest emission factor (129 g $CH_4$/kg input) which we used in the sensitivity analysis of this study according to precautionary principle. This emission factor is very high but on the other hand the default emission factor might be too low because of sub-optimal decomposition of organic material in hot and humid conditions.

### 3.3. Allocation calculations

In the sensitivity analysis 6 we investigated how an economic allocation between coffee and Inga tree fruit would affect our results. The yield of agroforestry coffee was 2.1 t $ha^{-1}$ and the yield of inga tree fruits 8.5 t $ha^{-1}$ (Acosta-Alba et al. 2020). We took the local price of inga tree fruit, 13.90 \$ $kg^{-1}$ and 7 \$ $kg^{-1}$ from two Colombian websites (Nativo Alimentos, 2024; Kairos comercializadora, 2024) and used the average of them (10.45 \$ $kg^{-1}$) in our calculations. For coffee we used the current (20.1.2025) reference domestic price of dry parchment coffee, 2 732 \$ 125 $kg^{-1}$, in our calculations, although this price varies based on travel distances from the farm to the point of purchase (FNC 2025). We multiplied the yields of coffee and Inga tree fruit by their prices to calculate the value of the crops from one year. This resulted in an economic-based allocation ratio of 1.94:1 for biodiversity impacts, so 34% of all impacts were allocated to coffee as the value of Inga tree fruits produced per ha was 1.94-fold compared to the value of coffee produced per ha. It must be noted, though, that the prices of coffee and Inga tree fruits may vary at different times. Also, the price of coffee and Inga tree fruit are not totally comparable to each other as the price of coffee covers the coffee itself and a coffee collection service for the producer, so there is no retail value added (FNC 2025), but the price of Inga tree fruits is a retail price.

### 3.4. Calculation of biodiversity impacts via ecotoxicity

The sensitivity analysis 7 considered possible biodiversity impacts through ecotoxicity. The inventory data for ecotoxicity calculations is presented in Table S2. We, however, did not consider the ecotoxicity impacts of background processes.

**Table S3.** Metal emissions to soil per 1 kg of parchment coffee (Acosta-Alba et al. 2020). Np = non-productive stage, P = productive stage.

| | **Conventional coffee** | | **Coffee agroforestry** | |
|---|---|---|---|---|
| **Emissions to soil** | **Np** | **P** | **Np** | **P** |
| Cadmium [mg kg$^{-1}$] | 0.0022 | 0.047 | 0.0042 | 0.029 |
| Copper [mg kg$^{-1}$] | 0.21 | 4.83 | 0.23 | 2.09 |
| Zinc [mg kg$^{-1}$] | 0.99 | 25.7 | 0.88 | 9.76 |
| Lead [mg kg$^{-1}$] | 0.079 | 1.293 | 0.12 | 0.81 |
| Nickel [mg kg$^{-1}$] | 0.26 | 4.17 | 0.42 | 2.69 |
| Chromium [mg kg$^{-1}$] | 3.54 | 17.3 | 8.34 | 37.9 |
| Mercury [mg/kg * 10$^{-6}$] | 0.46 | 0 | 0.22 | 1.98 |

For the metal emissions to soil we chose metal ion flows to soil from the ecoinvent database because ecotoxicity characterization factors (CFs) are available for metal ions in LC-IMPACT method (Verones 2021). For chromium emissions to soil there were CFs available for two forms of chromium: Cr(III) and Cr(VI) and their CFs have a great difference in magnitude (Verones 2021).

Chromium can end up in soil from agricultural inputs such as fertilizers, limestone and manure (Testa 2004). Also, some pesticides contain chromium (Testa 2004; Li et al. 2020). In this study we assumed that the chromium emissions to soil result from the application of fertilizers and lime as there are no pesticide inputs in the studied coffee cultivation systems. To calculate the ecotoxicity impacts of chromium we calculated how much of the total chromium emissions to soil (Table S2) is in the form of Cr(VI) and Cr(III). We took the share of Cr(VI) in compost and inorganic fertilizers from Krüger et al. (2017) study that analysed the content of Cr(VI) and total Cr in primary and secondary fertilizers. In their study the share of Cr(VI) from the total Cr content in triple super phosphate was 0.70 % and in potassium chloride and magnesium salt mineral fertilizer 1.67 % (Krüger et al. 2017). We used the average of these, 1.19 %, in this study as the share of Cr(VI) for inorganic fertilizers. The share of Cr(VI) in compost was defined by calculating the average Cr(VI) content from the 13 secondary fertilizers investigated in Krüger et al. (2017) study, and the result was 1.94 %. The rest of the chromium in total Cr content is Cr(III) (Krüger et al. 2017).

As in the inventory data the amounts of used inorganic fertilizers were straight as masses of N, P and K and not as the masses of different kind of fertilizer chemicals or fertilizer mix, we also calculated the shares of Cr(III) and Cr(VI) from inorganic fertilizers and compost based on the masses of N, P and K. From compost mass we only included the share of manure (20 %) in our calculations because as the rest 80 % is coffee pulp produced on the farm (Acosta-Alba et al. 2020), we assumed that this share of compost does not increase the metal emissions to soil when ending up back to the field. Acosta-Alba et al. (2020) estimated that compost input in the productive phase of CPS coffee cultivation system (5 t/ha) represents 25 kg of N per year. Thus, we concluded that the N content of compost was 0.5 %. In Acosta-Alba et al. (2020) study the P and K content of the compost was not defined and thus we searched them from literature. In Zhen et al. (2021) study the $P_2O_5$ content of composted poultry manure was 1.83 % and $K_2O$ content was 1.72 %. We used these numbers in our study after dividing the content of $P_2O_5$ with 2.29 and $K_2O$ with 1.20 to transform them to P and K content respectively. The mass of P and K in compost was then calculated by multiplying the mass of compost input by the share of these nutrients in compost.

We calculated the amount of Cr(III) and Cr(VI) in the chromium emissions to soil from inorganic fertilizers and lime by multiplying the Cr(III) and Cr(VI) content of primary fertilizers by the chromium emission to soil and the mass-% of inorganic fertilizers and lime from the total nutrients added to the field (99.4% for conventional coffee and 95.8% for agroforestry coffee), so inorganic fertilizers, lime and nutrients from compost. Similarly, we calculated the amount of Cr(III) and Cr(VI) in the chromium emissions to soil from compost by multiplying the Cr(III) and Cr(VI) content of secondary fertilizers by the chromium emission to soil and the mass-% of the nutrients in compost input from the total nutrients added (0.6% for conventional coffee and 4.2% for agroforestry coffee). Then we summed up the mass of Cr(III) from inorganic fertilizers + lime and compost as well as the mass of Cr(VI) from inorganic fertilizers + lime and compost.

## 4. Results of the sensitivity analysis 1-5

The numeric values for the results of sensitivity analysis 1-5 are presented in Table S2.

**Table S4.** Numeric values for the results of sensitivity analysis 1-5. OR = original results, SA = sensitivity analysis results, TE = terrestrial ecosystems, FE = freshwater ecosystems, ME = marine ecosystems.

| | Agroforestry, OG | Agroforestry, SA | Conventional, OG | Conventional, SA |
|---|---|---|---|---|
| **Sensitivity analysis 1** | | | | |
| Land stress impact [PDF•y] | 4.55E-13 | 4.42E-13 | 6.43E-13 | 6.18E-13 |
| Total impact on TE [PDF•y] | 6.66E-13 | 6.53E-13 | 1.15E-12 | 1.13E-12 |
| **Sensitivity analysis 2** | | | | |
| Land stress impact [PDF•y] | 4.55E-13 | 4.59E-13 | 6.42E-13 | 8.37E-13 |
| Total impact on TE [PDF•y] | 6.66E-13 | 6.70E-13 | 1.15E-12 | 1.35E-12 |
| **Sensitivity analysis 3** | | | | |
| Land transformation impact [PDF•y] | 2.60E-15 | 1.27E-12 | 2.98E-15 | 1.80E-12 |
| Total land stress impact [PDF•y] | 4.55E-13 | 1.72E-12 | 6.42E-13 | 2.44E-12 |
| Total impact on TE [PDF•y] | 6.66E-13 | 1.93E-12 | 1.15E-12 | 2.95E-12 |
| **Sensitivity analysis 4** | | | | |
| *TE* | | | | |
| Climate change impact [PDF•y] | 1.31E-14 | 3.34E-14 | 1.76E-14 | 2.18E-14 |
| Total impact on TE [PDF•y] | 6.66E-13 | 6.86E-13 | 1.15E-12 | 1.16E-12 |
| *FE* | | | | |
| Climate change impact [PDF•y] | 4.09E-15 | 1.04E-14 | 5.46E-15 | 6.78E-15 |

| | | | | |
|---|---|---|---|---|
| Total impact on FE [PDF•y] | 1.42E-14 | 2.05E-14 | 2.18E-14 | 2.31E-14 |
| **Sensitivity analysis 5** | | | | |
| *TE* | | | | |
| Land stress [PDF•y] | 4.55E-13 | 6.37E-13 | 6.42E-13 | 6.42E-13 |
| Acidification [PDF•y] | 1.97E-13 | 2.76E-13 | 4.92E-13 | 4.92E-13 |
| Climate change [PDF•y] | 1.31E-14 | 1.84E-14 | 1.76E-14 | 1.76E-14 |
| Total impact on TE [PDF•y] | 6.66E-13 | 9.32E-13 | 1.15E-12 | 1.15E-12 |
| *FE* | | | | |
| Climate change [PDF•y] | 4.09E-15 | 5.72E-15 | 5.46E-15 | 5.46E-15 |
| Water stress [PDF•y] | 7.02E-15 | 9.82E-15 | 1.09E-14 | 1.09E-14 |
| Freshwater eutrophication [PDF•y] | 3.08E-15 | 4.32E-15 | 5.46E-15 | 5.46E-15 |
| Total impact on FE [PDF•y] | 1.42E-14 | 1.99E-14 | 2.18E-14 | 2.18E-14 |
| *ME* | | | | |
| Marine eutrophication [PDF•y] | 3.30E-17 | 4.62E-17 | 4.85E-17 | 4.85E-17 |

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