Master's Thesis

Life Cycle Assessment and Biodiversity Impact Assessment of Organic Cocoa from the Dominican Republic

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Abstract: Global demand for cocoa is increasing. Over the last 20 years, production has almost doubled which leads to two primary problems: For the cultivation of the tropical tree, forests are often cleared for cultivation, which leads to high GHG emissions. Cocoa is also mostly cultivated in areas with high biodiversity, which further drives global biodiversity loss. As climate change progresses, suitable growing areas become increasingly scarce and pressure on the remaining forests and biodiversity hotspot areas increases. These issues are pushing for more sustainable cocoa. One such solution could be cocoa cultivation in organic agroforestry systems. While such systems are considered to have higher biodiversity and positive effects to micro-climate and soil quality, yields are often lower compared to monoculture systems, resulting in a higher land use to produce the same amount of cocoa. Goal of this study was to perform a Life Cycle Assessment (LCA) and investigate the environmental impact of organic cocoa from the Dominican Republic from 47 producers of 3 different regions and compare the results with other studies. The functional unit was defined as 1 kg fermented and dried organic cocoa from the Dominican Republic in the port of Antwerp (BE) and included all processes along the life cycle from production, fermentation, drying and transportation. The global warming potential according to IPCC (IPCC, 2021) from the average cocoa production of the study is 2.80 kg CO_2-eq/kg with land use change (LUC) related emissions having a share of 89%. The results were strongly influenced by a few outliers with high emissions caused by land transformation from forests. Within the regions, Transportation had a share of up to 67% of the total Global warming potential (GWP), drying with gas up to 23%. The total environmental impact according to the ecological scarcity method according to Frischknecht et al. (2021) is 307'000 ecopoints. 92% of the impact derives from land use related potential species loss. Measures such as preventing deforestation, increased reforestation, maximizing yields with improved farm management or reduced use of gas drying could significantly reduce the environmental impact with increasing benefits for both humans and the environment.

Keywords: LCA, Organic Cocoa, Environmental impact, Biodiversity, Land use change, Dominican Republic, GWP

1 INTRODUCTION

Cocoa is an important commercial crop in the tropics. Around 4 to 5 million tons are produced each year. The ivory coast and Ghana have a share of 60% of the worldwide production (OECD & SWAC, 2007). Worldwide, demand for this commodity is increasing with an annual growth rate of 3.44% from 2014 to 2019 (IISD, 2022). Since the sixties, the global demand for cocoa and chocolate has more than tripled. Even in the last 20 years production has almost doubled (ICCO, 2023). Especially Asian and African countries have shown a significant increase in demand (Recanati et al., 2018). Most of it is produced with conventional methods in monoculture systems. Growing at an estimated annual rate of 9.5% during 2021-2026 to 130'000 tons (Meier et al., 2020), Organic cocoa is slowly gaining more share on the world market. Nevertheless, with a share of around 3% organic cocoa remains a niche product (Lazzarini et al., 2022). In a global comparison, the Dominican Republic is a small producing country. According to the Inter-American Institute for Cooperation on Agriculture, a total of 150'000 hectares are managed by 40'000 producers. But the Dominican Republic has the biggest share in organic cocoa production. Around 60% of its cocoa exports are organic (2022). Since 1990 its cocoa production has almost doubled to 78'000 tons in 2020 with an average annual yield of 400 kg per hectare (FAOSTAT, 2023). Currently, cocoa is grown on 6% of all agricultural area in the Dominican Republic. It is the second most important crop after sugar cane (FAOSTAT, 2023). Over the last 20 years, the Dominican Republic has increased its forest area by 14% (1998 to 2018). This is mostly due to the intensive reforestation programme implemented by the Dominican Government (UNEP, 2023). At the same time, total cultivation area for cocoa has increased by 5%. According to data from FAOSTAT (2023) additional cultivated area was at the expense of perennial crop (80%) and annual cropland (20%). Even though the total forest area has increased, individual cultivation fields might be at risk of converting native forest into cocoa plots, which leads to high land use change related CO_2-emissions.

Another negative effect of land use change is the loss of biodiversity. The five main direct drivers of global biodiversity loss are climate change, pollution, invasive species, direct exploitation or land use change (Damiani et al., 2023). Globally, land use change is the direct driver with the largest relative impact on terrestrial ecosystems and responsible for roughly 30% of biodiversity impact (2019). According to the Living Planet Report by WWF, habitat degradation and loss is responsible for almost 50% of species loss for taxas birds, reptiles and amphibians (2022b). Global biodiversity is declining at an alarming rate: It is estimated that the rate of species loss in the last 50 years is higher at a factor of 100 to 1'000 compared to the past 10 million years with a decline in wildlife population of 60% on average between 1970 and 2014 (WWF, 2022b). Latin American and Caribbean regions show even a higher decline of 94% (WWF, 2022a). According to the intergovernmental science-policy platform on biodiversity and ecosystem services (IPBES), global biomass of wild mammals has fallen by 82% since prehistory (2019). According to World Wide Fund for Nature (WWF), 1% to 2.5% of all birds, mammals, amphibians, reptiles and fish have already gone extinct (2022a), leading to a possible decrease in the functioning of ecosystems and threatening their stability and reduce ecosystem services (Cardinale et al., 2012). Hoang et al. (2023) state that on a global level, a third of all agricultural production occurs on high conservation preservation areas. Cocoa is almost exclusively grown in high conservation priority regions. Especially in the Dominican Republic with its high share of endemic species, cocoa production has the potential to put many species at risk of extinction (Hoang et al., 2023). According to the Ministry of Environment and Natural Resources of the Dominican Republic, 96% of amphibians, 89% of reptiles and 34% of vascular plants occurring in the Dominican Republic are endemic (2012). Many of these species have a narrow range and live in specific niche environments (CEPAL, 2018). According to the Critical Ecosystems Partnership Fund (CEPF) the Dominican Republic has 35 key biodiversity areas covering 18% of the country's territory. Such areas are of global significance for biodiversity conservation and require high protection due to their uniqueness and vulnerability (Langhammer et al., 2018). Even though high-income countries as Switzerland are not directly involved in cocoa production, they consume more than 50% of high-conservation risk products as cocoa and coffee (Hoang et al., 2023). Looking at the Swiss final consumption, biodiversity footprint increased by

8% between 2000 and 2018. While the domestic footprint decreased by 22%, the foreign share of the footprint increased from 58% to 70%. (Nathani et al., 2022). Based on the planetary boundary principles, the Swiss biodiversity footprint should be reduced by 74 %.

The above-mentioned issues push for sustainable farming practices that generate high yields and income for producers with the lowest possible pressure on the environment. Part of the solution could be agroforestry systems, which, in the long term, provide higher yields and a diversified income in the long term. Furthermore, such agroforestry systems can play a crucial role in providing a higher biodiversity than monoculture systems by preserving up to 46% of forest tree species. Maney et al (2022) investigated biodiversity intactness in different cocoa cultivation systems from 36 studies covering 1300 sites. The range of outcome varies largely between different regions and systems. Compared to a primary forest, biodiversity intactness is on average 22% lower in forest derived agroforestry systems and 45% lower in open land derived agroforestry systems. A conversion from open land systems to agroforestry systems on average led to a 14% higher biodiversity intactness. Furthermore, according to Parra-Paitan & Verburg (2022), global extinction rate in agroforestry systems was 65% lower compared to full-sun cocoa systems. Bandanaa et al. (2021) came to the same conclusion with a 26% higher species diversity and 24% higher genetic diversity compared to conventional systems. On the downside, agroforestry systems often have lower yields compared to intensive monoculture systems, requiring more land to produce cocoa. In the long run, however, and taking into account side yields from other fruits, yields are often equivalent or higher (Pérez-Neira et al., 2020; Saj et al., 2017).

For the Swiss-based cocoa trading company Pronatec, which follows such agroforestry practices in the Dominican Republic, the environmental impact of its cocoa is of great interest. To be able to take measures to reduce the environmental impact, it must first be quantified. Subject of this study is cocoa from the Dominican Republic, grown in 3 different regions by small-scale producers in agroforestry-systems, according to organic and fair-trade standards (2023a). The goal of this study is to examine the occurring environmental impact of the different processes cultivation to fermenting, drying packaging and its overseas transportation to Europe. To classify the results, comparison with other studies and literature values will be done. Currently only few LCA studies exist regarding biodiversity impact from cocoa. No life cycle assessment has yet been carried out for cocoa from the Dominican Republic. Furthermore, there is no study in which cocoa is dried with gas. The influence of this process on the environmental impact is completely unknown. This study will fill this gap and provide insight into the environmental impacts of organic cocoa from. It will give a first indication of biodiversity impact for cocoa from the Dominican Republic. Based on the outcomes of this study, recommendations on improvement possibilities regarding the environmental performance of the study subject are presented.

2 RESEARCH METHODOLOGY

The following chapter describes the applied methodology for this LCA. The LCA is performed according to the International Organisation for Standardisation (ISO) 14040 and 14044 (ISO, 2006, 2017). The LCA is divided into the four phases goal and scope definition, inventory analysis, impact assessment and interpretation.

2.1 GOAL AND SCOPE

The Swiss based company Pronatec has been trading organic cocoa products, sugar, vanilla, and different spices for over 30 years (2022). Pronatec imports around 4'600 tons of dried cocoa each year from the Dominican Republic. Yacao SRL is a subsidiary company of Pronatec that works with the smallholder organisation FUNDOPO (Pronatec, 2023b). These partnerships allow a direct and transparent supply chain. By now, the organisation has grown to more than 3'000 producers. The data collection took place in three regions in the Dominican Republic: Medina (18°31'55.7"N, 70°08'19.9"W), Yamasa (18°46'39.0"N, 70°04'13.9"W) and Navarrete (19°35'48.0"N, 70°52'47.5"W) with an own processing centre each. Figure 1 illustrates the location of the 3 processing centres and the port of Santo Domingo. Navarrete is the biggest of the 3 centres with a share of 40% of all processed cocoa, followed by Yamasa (36%) and Medina (25%). Almost the same amount of cocoa was additionally processed via a third-party supplier and not via one of the 3 processing centres. After the completion of the data collection for this study, a new processing centre was opened in the region El Seibo (Pronatec, 2023a). Both, cocoa from this new processing centre as well as all cocoa from third-party suppliers is outside the system boundary and was not considered further. All cocoa is fairtrade and organic certified grown in agroforestry systems, where, in addition to cocoa, other plants such as avocados, citrus fruits, bananas or yams are grown (Pronatec, 2023d).Compared to full-sun monoculture systems, agroforestry systems have the advantage of providing a better micro-climate, better soil fertility, higher biodiversity and a more diverse income (Abada Mbolo et al., 2016; FiBL, 2017). Production is mainly on a small scale with only a few hectares per producer (Figure 21).

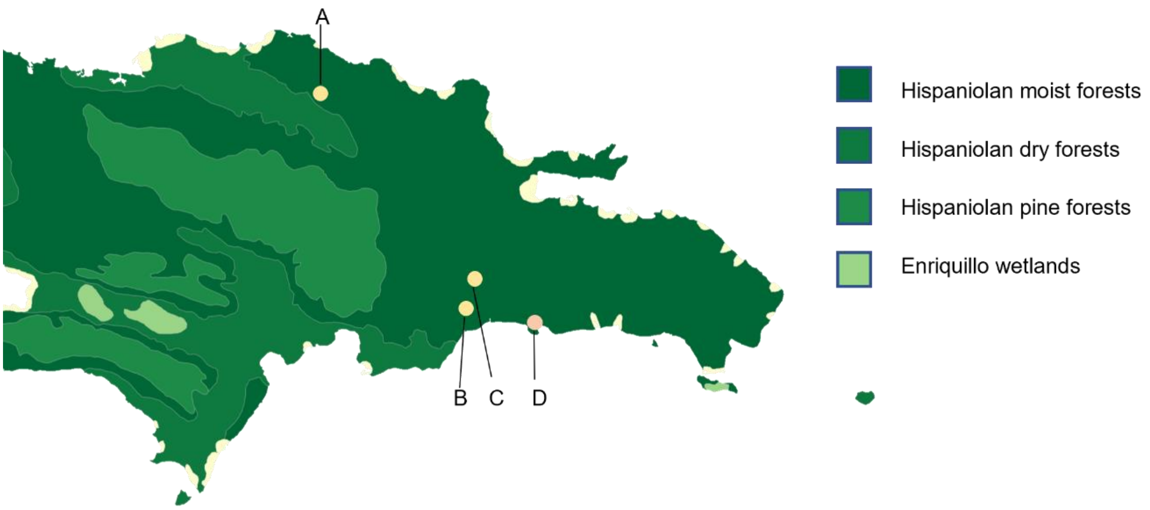

Figure 1 Overview of the regions surveyed for the assessment of the environmental impact of dried organic cocoa from the Dominican Republic. (A = Navarrete, B = Medina, C = Yamasa, D = Port of Santo Domingo), The ecoregions are coloured in different shades of green. Graph: Own illustration

The system boundary of this LCA study includes all processes from seedling production, transportation, fermentation, drying and ends with the arrival of the cocoa beans in the harbour of Antwerp, Belgium (BE), depicted in Figure 2. The functional unit leaves the system downwards and is defined as following:

«1 kg fermented and dried organic cocoa from the Dominican Republic in the port of Antwerp (BE)»

The system starts with the production of cocoa seedlings (Theobroma cacao) in the nursery in Medina. Only a small fraction of the seedling's origin from the nursery itself. The cocoa is organically grown besides side-crops as avocados, bananas, or citrus fruits in agroforestry-systems. The application of pesticides is prohibited but traces of pesticides can be detected in occasional samples. Tree branches are occasionally pruned back to optimize growth and productivity. Occasionally, bigger trees or branches are cut down with a chainsaw. Each tree produces multiple pods all year round, each containing up to 50 beans. During the harvest, the pods are separated from the tree with machetes and extracted. The pods are left on the field where they slowly decompose into humus. They are not further used and pose no economic value. Possible emissions from the fermentation process are not included since the pods are distributed evenly on the fields and it can be assumed that anaerobic decomposition is not happening. The beans are not ready for consumption yet and surrounded with a white, sweet tasting pulp. Then they are transported to an intermediary, mostly with a mule, motorcycle, or car, and temporarily stored in plastic containers. The fresh cocoa beans are transported in plastic bags of 60 kg each to one of the three processing centres in Medina, Yamasa or Navarrete where they are fermented in big plastic bags for 5 to 7 days. Next, the fermented beans are laid out on wooden planks under plastic foil to dry for around 7 days to a moisture content of around 7.5%. Around 20% of all beans are partially dried with a propane fuelled oven. If too much rain prevents sun drying in Yamasa, part of the cocoa from Yamasa is transported to Navarrete to fully dry. For the last step, all cocoa is transported to Medina, where a machine sorts out foreign matter such as sticks, plastic or small stones[1]. The beans are filled into bags of 60 kg capacity and packed into shipping containers of 25 tons capacity. Finally, the containers are transported to the port of Santo Domingo and loaded onto a containership for the transportation to Antwerp in Belgium (51°15'41.6"N, 4°14'14.3"E).

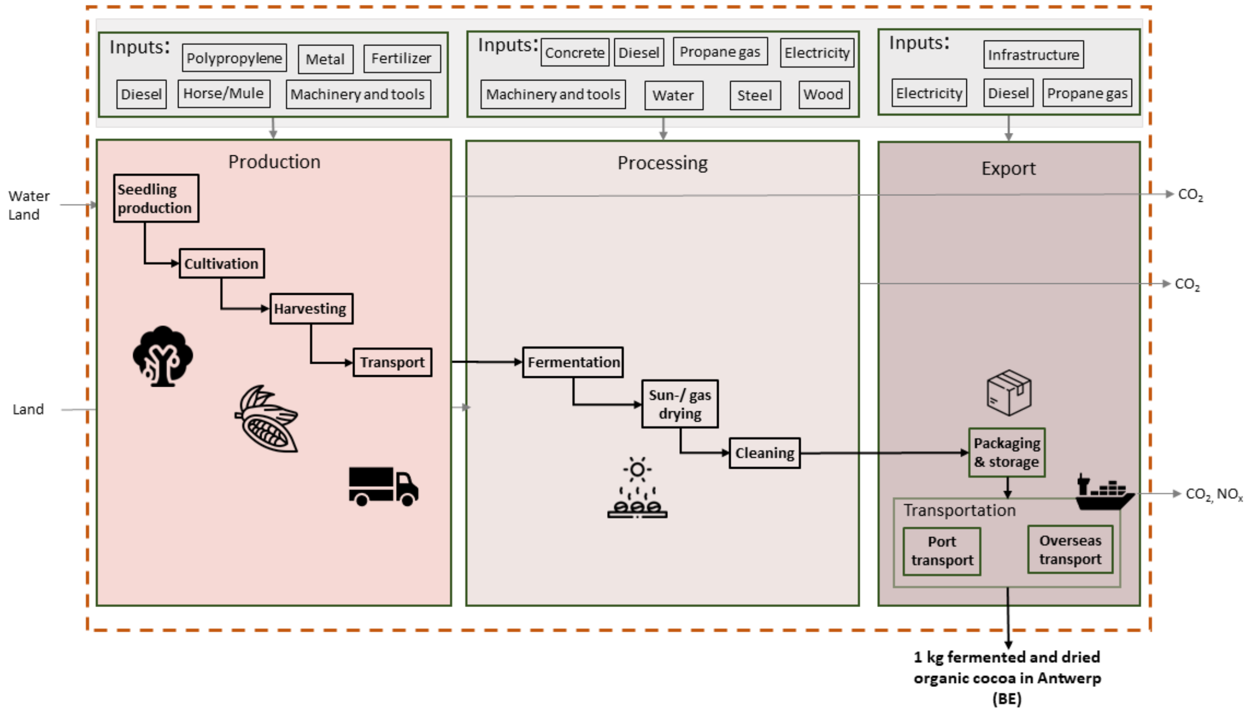

Figure 2 System model of the life cycle of organic cocoa from the Dominican Republic. The boxes represent the 3 main life cycle stages Production, Processing and Export. Vertical lines display product flows, horizontal arrows represent direct inputs from and outputs to the ecosphere. The beige box on top represents background processes. Icons: Adobe Stock (2023)

[1] *L. E. De León Frias, personal communication, 14 March 2022, Yacao SRL*

The statements refer to cocoa from the subsidiary Yacao SRL described in the system model with the calculations and assumptions given for the year 2021. The associated geographical conditions, different means and distances of transport and processing steps are context specific. Fluctuating yields and prices have an impact on aspects such as allocation and change results significantly. Based on the above stated conditions, the goal of this study was to assess the environmental impacts of organic cocoa from the Dominican Republic. The following three research objectives were defined:

- Identification of the environmental hotspot in the life cycle of Dominican organic cocoa
- Comparison of the results with organic cocoa from different countries
- Identification of potential for optimisation to improve the environmental performance

2.2 ALLOCATION

Allocation describes the assignment of input or output flows from processes to products if several products are created in one process. several products are produced in one process. In addition to cocoa, other fruits were also produced on the cultivation fields, either for own consumption or for resale. To allocate the environmental impacts, an economic allocation was made. The allocation factor depends on yields from cocoa and side crops and prevailing market prices. Both factors that fluctuate and are linked with uncertainty. Regardless, whether the harvested fruits were directly consumed or sold at the market, all side-crops were included and treated as potential income. Average market prices for side-crops were taken from the ministry of agriculture of the Dominican Republic (2022). In total, cocoa accounted for 53% of all income. Therefore, 53% of all crop-unspecific activities and inputs were allocated to cocoa, 47% to all side crops. To analyse the impact of the allocation factor, 2 scenarios were made to compare the outcomes: One with an allocation factor of 75%, a second one with an allocation factor of 100% (chapter 5.2Sensitivity Analysis).

2.3 INVENTORY ANALYSIS

For the data collection of this LCA study, both primary and secondary data were applied. Main source of information were quantitative interviews on-site. A total of 55 interviews were conducted: 51 cocoa producers were interviewed with a standardised questionnaire. 3 interviews were conducted for each of the 3 different processing facilities Medina, Yamasa and Navarrete, followed by a separate interview for the nursery in Medina. All interviews were conducted in Spanish over a period of 2 weeks in March and April 2022. The survey was accompanied by a staff member of the cooperative FUNDOPO to bridge language differences. Due to differences in regional terminologies, the questionnaire was adapted after the first day of data collection. Interviewees were chosen by the smallholder organisation (FUNDOPO) due to proximity, accessibility, and to ensure a certain variability in variables such as field size, age of producers or gender. To gain a better impression about the cultivation, producers in Medina were interviewed on their own plantations. Due to time constraints, for the second period of data collection, interviews were mainly conducted centralized at several cocoa purchase points. From a total of 51 interviewed producers, 4 were excluded from the assessment due to unrealistic values as too high yield per hectare. Unless otherwise stated, data is taken from internal Excel files of Yacao or Pronatec. Due to factors such as cocoa varieties or maintenance, Yacao has defined an acceptance rate which is set at a maximum of 800 kg of dry cocoa per hectare[2]. Therefore, cut-off was set at 800 kg. Hence, for the final assessment, information from a total of 47 producers (43 male, 4 female) are included. Pronatec provided specific information about the processing centres, transportation routes and general information specific processes along the life cycle. Such information was either collected from data sheets, by mail or personal communication during several phone calls or online-meetings. The life cycle inventory modelling and impact assessment were executed using the SimaPro software v9.4 (PRé Consultants, 2022). Secondary data was collected through literature research. For modelling of the background processes, the ecoinvent 3.9 database (system model: allocation, cut-off by

[2] R. Hipper, personal communication (Excel sheet “Productores Fundopo con GPS”, 28 January 2022, Yacao SRL

classification – unit) was used (ecoinvent Association, 2022) . Background processes and materials are visualized in the beige box at the top of the system model, seen in Figure 2.

2.4 IMPACT ASSESSMENT

The impact assessment for this LCA was carried out in SimaPro. To assess the environmental impact of one kg of dried organic cocoa, the impact assessment methods in Table 1 were applied. These methods were selected to adequately reflect the relevant environmental impacts from materials, fuel consumption, pesticides, and land use.

Table 1 Overview of all applied impact assessment methods in this LCA study

Indicator	Method	Source
Climate change	IPCC (2021)	(IPCC, 2021)
Potential Species Loss (PSL), Potential damaged fraction (PDF)	Land use biodiversity (2018)	(Chaudhary & Brooks, 2018)
Total environmental impact (ecopoints)	Ecological Scarcity (2021)	(Frischknecht et al., 2021)

Global warming potential (GWP 100a): The assessment for all Climate change related emissions was performed using the method IPCC 2021 GWP 100a by the Intergovernmental Panel on Climate Change (IPCC, 2021). The potential climate impact of greenhouse gases is compared with the climate impact of CO_2 and expressed in CO_2 equivalents. The method can be assessed on different time horizons (20, 100 and 500 years). In this study a time horizon of 100 years is used as recommended by the Life Cycle Initiative. IPCC is the most acknowledged institution regarding climate change science (IPCC, 2022).

Land use biodiversity (2018): The method of Chaudhary & Brooks (2018) is an updated version of the method from Chaudhary et al. (2015). It is recommended by the UNEP-SETAC for assessing biodiversity impact (Koellner et al., 2013). All occurring species loss is attributed to land use and land use change. Other drivers such as climate change, pollution, overexploitation, or invasive species are not included. The method provides global characterisation factors (CF) for 5 taxa, namely mammals, birds, amphibians, reptiles, and plants. Characterisation factors arise from a combination of countryside species-area-relationship (SAR) and vulnerability score, indicating the endemic richness of an ecoregion and the species threat level according to the International Union for Conservation or Nature (IUCN) Redlist (IUCN, 2020). Characterisation factors differ for 5 broad land use types (managed forests, plantation forests, pasture, cropland, urban) under three intensity levels (minimal, light, intensive). The agroforestry organic cocoa systems from this study can be characterised as cropland under minimal intensity level, since low intensity is defined as little or no application of fertiliser, pesticides, ploughing, irrigation and mechanisation (Chaudhary & Brooks, 2018). The method provides CF for 804 terrestrial ecoregions from Olson et al (2001). With the implemented method in SimaPro, characterisation factors are only available on country level which is the aggregated sum of ecoregion factors and their relative share on land area in each country. To obtain a higher accuracy, the calculation with the ecoregion factors was carried out in the provided in the supporting information of the study of Chaudhary & Brooks. Biodiversity damage is expressed as global extinctions of species, in the units of potential species-equivalence loss (PSL), or potential disappeared fraction of species (PDF), representing the projected taxa aggregated fraction of species going extinct. The method provides characterisation factors for both, land transformation and land occupation. In this study, only biodiversity impact due to land occupation will be assessed. Biodiversity impacts arising from land transformation will not be assessed. This method was chosen due to the expected high biodiversity impact from cocoa cultivation. As no other life cycle assessments, applying this method on the cultivation of cocoa, exist, this study will be the first to assess biodiversity loss from land use for cocoa.

The potential global species loss for 1 kg of cocoa is obtained by applying the following equation:

Allocation factor * taxa specific ecoregion CF * m^2/FU

The potential global disappeared fraction of species for 1 kg of cocoa is obtained by applying the following equation:

Allocation factor * taxa aggregated CF * m^2/FU

Ecological Scarcity 2021: The single score method Ecological Scarcity (2021) uses different impact categories and is expressed in ecopoints. It is a target-based method, based on non-objective valuations and weighting factors based on political target values and therefore not compliant with ISO-standards. It measures the environmental damage in a comprehensive and aggregated single score value (ecopoints) per unit of quantity. In the context of this study, the Ecological Scarcity (2021) was applied for its comprehensible and aggregated single score value allowing a comparison with the environmental footprint of Switzerland, commissioned by the Federal Office for the environment FOEN (Nathani et al., 2022).

2.5 LAND USE CHANGE

Globally, land use change (LUC) related greenhouse gas (GHG) emissions are one of the main contributors to climate change, accounting for 13-21% of global total anthropogenic GHG emissions (2010-2019), with deforestation being responsible for around 45% of those emissions (IPCC, 2021). In addition to being a net carbon sink and source of GHG emissions, land plays an important role to climate through evapotranspiration, albedo effect and aerosol loading (UNFCCC, 2023).

The principle of direct land use change was introduced by the Intergovernmental Panel for Climate Change (IPCC) Guidelines (2006). It allocates all emissions from land transformation activities to each year of land use homogeneously over a defined period after which the transformation happened. For this study, land use change related emissions are considered for a period of 20 years This time span is chosen because it is used as default by the Intergovernmental Panel for Climate Change (IPCC) Guidelines. To address the influence of the chosen time span for the emissions, an uncertainty analysis for land use change will be carried out with a time span of 50 years.

To determine the land use change related CO_2-emissions, the LUC Impact tool (version 2021) by Blonk consultants was used (2021). Within the tool, land use change related CO_2-eq emissions indicate the difference in stored carbon in the reference situation (before cocoa plantation) and the stored carbon (C) in the established cocoa plantations. It includes soil carbon stock, vegetation carbon stock and dead organic matter carbon stock. The results are calculated based on the following indicators:

Selected crop:	*Cocoa*
Selected country:	*Dominican Republic*
Climate:	*Tropical, moist*
Soil type:	*HAC soils*
Cultivation tillage intensity:	*No-tillage*
Cultivation input level:	*Low*

Based on these inputs, the resulting total carbon stock in cocoa plantations is 81 t carbon per hectare. Soil carbon stock is 66 t C/ha and vegetation carbon stock is 14 t C/ha.

2.6 INTERPRETATION

The last phase of the LCA describes the interpretation, where the results are summarised, discussed and conclusions and recommendations are drawn. To test the reliability and robustness of the results, sensitivity analyses are carried out. Scenarios help to check whether conclusions are drawn correctly according to the ISO 14044 standard and how a change in parameters can has an influence on the results. The following 3 scenarios were conducted:

- Different allocation factors (53%, 75% and 100%)
- Different time frame for land use change (20 years & 50 years)
- Overall uncertainty analysis (Monte-Carlo Analysis)

3 LIFE CYCLE INVENTORY ANALYSIS

The system was modelled according to the goal and scope, described in chapter Goal and Scope. The modelling for 1 kg of dried cocoa was performed in three main steps, namely fresh cocoa, fermented cocoa, and dried cocoa. For obtaining 1 kg of dried cocoa, a total of 2.8 kg fresh cocoa is needed on average. During the fermenting process, fresh cocoa will lose 25% of its weight, resulting in 2.1 kg of fermented cocoa[3]. The fermenting process will lead to another weight reduction of 52%, resulting in 1 kg dried cocoa. The inventory analysis is divided according to these 3 main steps. Where no data for processes and material demands were available, assumptions and estimations had to be made. Detailed tables with calculations, assumptions and estimations on the life cycle inventory models can be found in the supplementary material (appendix O, starting on page 54). Table 2 gives an overview of the key parameters of the cultivation areas.

Table 2 Key parameters regarding the investigated cultivation areas from the areas Medina, Yamasa and Navarrete in the Dominican Republic from a total of 47 producers.

Parameter	Unit	Medina	Yamasa	Navarrete	Total
Number of plots considered	p	17	12	18	47
Total harvested fresh cocoa	t	72	155	489	716
Covered area	ha	73	99	357	529
Median area/producer	ha	2.5	6.6	10.9	4.4
Median yield per hectare	kg	360	518	431	428
Mean income share of cocoa	%	47	59	56	53

Yields are heterogenously distributed amongst the processing centres, as seen in Figure 3. Minimum values vary between 89 kg/ha*y in Medina and 262 kg/ha*y in Navarrete. Medina has the lowest median value with 360 kg/ha*y, Yamasa has the highest median value with 518 kg/ha*y. The median value of the average is 428 kg/ha*y. The maximum yield was 750 kg/ha*y in all three regions.

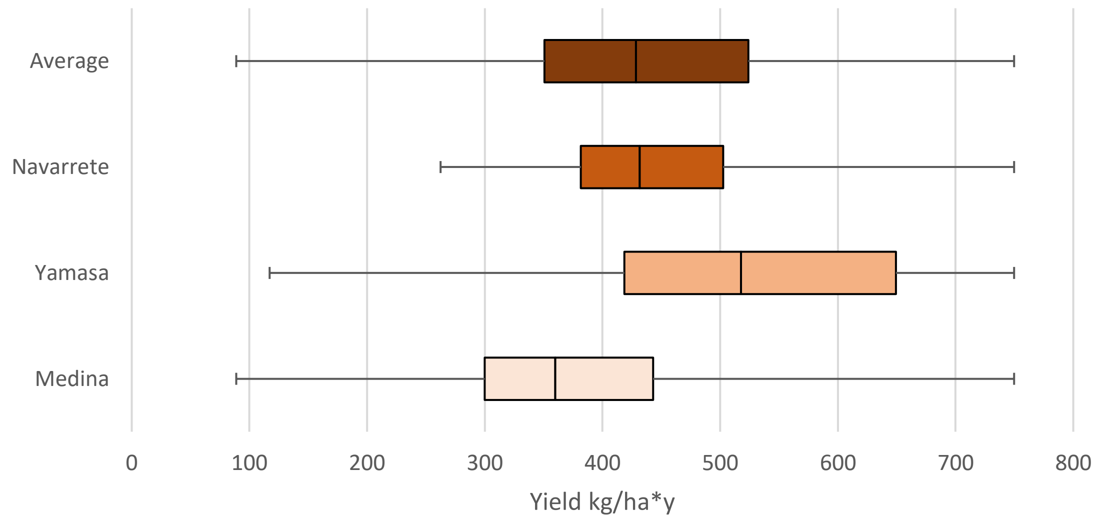

Figure 3 Boxplot of the yields for fresh cocoa per hectare for the 3 processing centres Medina, Yamasa and Navarrete and Average yields in the Dominican Republic. 50% of the values for the yields are within the coloured boxes. The lines within the boxes mark the median value, the bars show the minimum and maximum values.

[3] *R. Hipper, personal communication, 05 September 2022, Yacao SRL*

Table 3 gives an overview of the key figures for each processing centre (Medina, Yamasa and Navarrete) and the combined values, stated as “Average”. In 2021, a total of 2’167 tons of dried cocoa was exported directly to Europe. All direct export is handled through a third-party supplier and do not go through the processing centres of Yacao. Direct export is excluded in this study and not further considered.

Table 3 Key figures of the 3 processing centres Medina, Yamasa and Navarrete and the combined value, stated as “Total”. Direct export of dried cocoa is handled through a third-party supplier and is not handled via the Yacao’s own processing centres.

Parameter	Unit	Medina	Yamasa	Navarrete	Total	Direct export
Dried cocoa	t/y	590	847	948	2’385	2’167
Share of dried cocoa	%	25	36	40	100	
Gas-drying oven		Yes	Yes	No		
Packaging machine		Yes	No	No		

Fresh cocoa: According to all producer statements, no form of pesticides or herbicides were applied. Nevertheless, a share of below 2.7% of all samples of dried cocoa in Switzerland show traces of substances such as Glyphosate, 2,4-D and Chlorpyrifos[4] at a level close to the detection limit. The use of the latter is prohibited in the European Union (European Commission, 2019). Concerning the contamination with pesticides, it was not possible to distinguish whether the contamination was from prohibited direct application or cross contamination from other farmers and institutions. For the modelling of the average environmental impact, the pesticide contamination was assumed as being fully sourced from application by farmers. The rate was taken from information provided by the pesticide producing companies. Emissions ratios into air, water and soil were taken from other ecoinvent datasets. For 2,4-D and Chlorpyrifos, ratios were taken from dataset *Maize, at farm/US-NC Economic.* Emissions ratio for Glyphosate was taken from dataset *Coffee, green bean {HN}| coffee green bean production, arabica | Cut-off, U.* Power sawing for pruning trees and cutting down old, ill, or unwanted shade trees was rarely used. If applied, producers have either indicated total application time or amount of petrol used. Based on the interviews, the total use of chainsaw was 47.4 hours for 716 tons of cocoa.

According to producer statements during the interviews, most of the cocoa trees grow naturally without producers planting any seedlings. Cocoa seedlings from the cooperative or another supplier are rarely distributed. For producers that have received seedlings only once, it was assumed that the same number of seedlings are being received at intervals of 10 years. The orchard consists of several, tunnels, each measuring 4x37.5m. An assumed 5 cm layer of gravel serves as foundation. A metal structure, covered with a close-meshed polypropylene net protects the plants from the weather. For both materials, an assumed lifetime of 20 years is taken. The seedlings are assumed to be 6 months in the nursery and watered every second day with 0.5 l for each seedling (Afrimash, 2023). Before leaving the nursery, the seedlings are packed in polyethylene plastic bags.

Cocoa from plantations in remote areas without sufficient road infrastructure is often transported by horse or mule to the intermediary or the next storage point. The animals are often owned by the producers itself or rented for transport purposes. For horses a lifetime of 25 years was assumed with a carrying capacity of 80 kg, being 15% of the animals weight (SVPS, 2022). A maximal daily transporting distance of 15 km was assumed. For mules a lifetime of 35 years was assumed with a carrying capacity & utilisation of 85 kg as well as a maximal daily transporting distance of 15 km. Methane emissions

[4] *N. Merky, personal communication, 05 September 2022, Pronatec AG*

from horses (18 kg/y) and mules (14 kg/y) were taken from IPCC Guidelines for National Greenhouse Gas Inventories (2006). Feed intake was calculated with an assumed share of 80% grass and 20% maize feed (Tiergesund.de, 2016). The modes of transport and distances from the plantation to the intermediary or to the intermediate storage were obtained by means of a questionnaire. Some cocoa is temporarily stored in polypropylene containers with a capacity of 150 litres. A lifetime of 10 years was taken according to producer statements.

Fermented cocoa: The fresh cocoa is transported from the intermediary to one of the 3 processing centres with a small lorry over an average distance of 21 km. For the transportation, white polyethylene bags with a capacity of 60 kg are used. Each bag is used twice on average, before disposed[5]. A total of 750 polyethylene bags, measuring 2 kg each, are used per year for the fermentation of all cocoa in the 3 centres. The washing of all fermentation bags is usually done with a custom-built washing machine in Navarrete. Since it did not work for some time, energy and water consumption could not be measured. To bridge the gap, the bags are washed by hand, with a water consumption of 1 kg per kg laundry, approximated with an ecoinvent dataset (*Washing, drying and finishing laundry {GLO}| washing, drying and finishing laundry | Cut-off, U)*. The fermentation building, measuring a total of 590 m^2, is an open structure building with a concrete foundation, steel-reinforced concrete poles, and a corrugated aluminium roof. The lifetime for the materials of the fermentation building were included in the statements of the questionnaires and can be found in the supplementary materials (Table 14).

The fermented beans are laid out under 2 types of drying tunnels. The ground structure consists of wooden planks, wooden posts, and a plastic foil roof. The second type consists of a wooden planks floor, metal posts and a corrugated metal roof. It is assumed that both types of tunnels are applied 50% each. Due to only slight differences and expected minor impacts of the tunnel infrastructure, the modelling was done based on the infrastructure and respective amounts of cocoa for the region Yamasa and extrapolated for all three regions.

Propane gas is used for the operation of forklifts, the drying oven and generator for the packaging machine. It is calculated with a density of 0.506 kg/l according to the Swiss Liquefied Petroleum Gas Association (2023) and a heating value of 46.46 MJ/kg, taken from the ecoinvent dataset "*Propane, burned in building machine {GLO}| propane, burned in building machine | Cut-off, U*". The propane gas consumption for the drying of cocoa was measured in a period between 25th of January 2022 and 10th of February 2022 in Yamasa. A total amount of 13'150 kg of cocoa was dried, consuming a total of 593 litres propane gas, being equal to 0.045 litres propane gas per kg cocoa[6].

For the operation of the forklifts, a propane consumption of five gallons per day in high per forklift was indicated by Yacao. Off-season consumption was significantly lower. For the modelling, 2 running forklifts in each of the three centres with a daily consumption of 2.5 gallons (50% consumption compared to the consumption in high season) per vehicle and day and a maximum operating time of 10'000 hours were calculated. The propane gas powered forklift is used for transporting the goods on site for short distances. It was modelled using an ecoinvent dataset for agricultural trailer as basis (*Agricultural trailer {CH}| production | Cut-off, U),* adjusting the weight to 2.7 tons (Toyota, 2023).

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[5] *L. E. De León Frias, personal communication, 14 March 2022, Yacao SRL*
[6] *J. Joselyn, personal communication, 18 March 2022, Yacao SRL*

The packing machine is run by a propane gas powered generator, consuming 50% of its energy[7]. The packing of a container of 25 tons takes 7 hours, consuming a total of 62.3 litres[8]. Hence, a total of 31.15 litres propane gas is attributed to the packing machine. As the basis for the modelling of the packaging machine, an ecoinvent dataset was used (*Building machine {RER}| production | Cut-off, U*) and adjusted accordingly. The machine was assumed to weigh 1 ton with a lifetime of 15 years. The packaged and dried cocoa is transported a total distance of 84 km by lorry to the port of Santo Domingo. The final step is the transportation of the dried cocoa beans from the port in Santo Domingo (DR) to Antwerp (BE). For the calculation of the distance, the platform SeaRates was used (SeaRates, 2022). A total of 1% of cocoa is lost during the whole process. Table 4 gives an overview of the different life cycle stages, the inputs, and data sources. Details can be found in the respective inventories in the supplementary material.

Table 4 Summary of the input data from the inventory analysis of 1 kg of dried organic cocoa. Listed inputs include data across all life cycle stages.

Life cycle stage	Component	Input	Data source
Fresh cocoa	Pesticides	Glyphosate	Secondary data
		2,4 Dichlorotoluene	Secondary data
		Chlorpyrifos	Secondary data
	Machines	Power sawing	Primary data
	Material	Cocoa seedlings	Primary data, estimations
		Polypropylene container	Primary data, estimations
	Transport	Horse / Mule	Primary data, assumptions
		Motor scooter	Primary data
		Passenger car	Primary data
Fermented cocoa	Transport	Lorry Primary data	
	Material	Fermentation bag Polyethylene	Primary data
		Packaging bag Polyethylene	Primary data
		Fermentation building	Estimations
		Washing of fermentation bags	Primary data, estimations
Dried cocoa	Material	Drying tunnel - Wooden construction - Metal construction	Primary data, estimations
		Sorting machine - Propane gas	Primary data, estimations
		Gas oven - Propane gas	Primary data, estimations
		EUR pallets	Primary data
		Packaging bag Polyethylene	Primary data
	Transport	Forklift	Primary data, estimations
		Lorry	Primary data
		Container ship	Primary data

Inventory of the alternative scenarios: For the allocation scenario, the modelled datasets from the base calculation were taken and adjusted where the allocation factor had an influence (see Table 13, Table 14, Table 15).

[7] *L. E. De León Frias, personal communication, 14 March 2022, Yacao SRL*

[8] *K. Moser, personal communication, 1 February 2022, Yacao SRL*

4 RESULTS

In the following chapter, the results will be displayed separately for 3 different impact assessment methods.

4.1 GLOBAL WARMING POTENTIAL (IPCC 2021, GWP 100A)

The production of 1 kg dried organic cocoa from the Dominican Republic leads to total emissions of 2.80 kg CO_2-eq. As shown in Figure 4, the result is dominated by land use change related emissions which contribute 2.49 kg CO_2-eq (89%) of the total GWP. Transportation contributes 7% due to the emission of carbon dioxide and methane from combustions. Within transportation, ship transportation and lorry contribute the most with 35%, respectively 34%. Transportation by car contributes 15%, the use of forklifts 10%. Mule and horse have a transport contribution of 6% combined due to methane emissions from digestion and emissions through the production of feed. Materials such as plastic bags and containers, wooden and metal structures often have a long lifetime or are used several times. They contribute 3% to the total GWP. Within this category, plastic bags have a share of 81% (0.05 kg), followed by pesticides with 10% (0.0065 kg), the sorting machine with 4% and seedlings with 1%. The drying process contributes 1% to the GWP due to the burning of propane gas. Drying tunnels contribute less than 1% due to the production of concrete and steel.

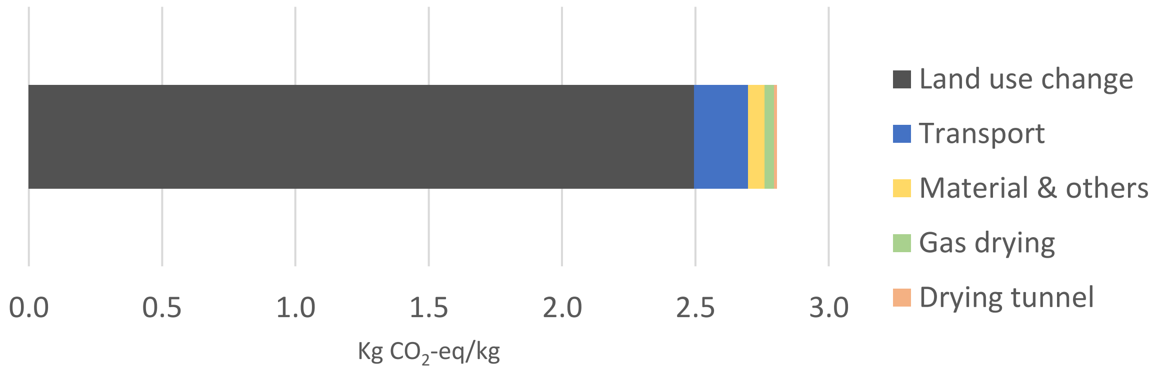

Figure 4 Average GWP of dried organic cocoa from the Dominican Republic (LUC 20y). The average GWP consists of 47 individual farms from three regions (Medina, Navarrete, Yamasa).

Figure 5 displays the average weighted GWP per kg of dried cocoa beans broken down into the 3 regions Medina, Yamasa and Navarrete. The results show significant regional differences. Navarrete has the highest GWP with emissions of 4.30 kg CO_2-eq. The GWP of Medina is 0.33 kg CO_2-eq emissions (-92%). With 0.30 kg CO_2-eq, Yamasa has a 93% lower average GWP compared to Navarrete. In Navarrete, LUC related total emissions are 4.02 kg CO_2-eq (93%), arising from 4 plots with emissions between 25 kg CO_2-eq and 52 kg CO_2-eq per kg cocoa, depicted in Figure 6. In Medina, LUC related emissions of 0.05 kg CO_2-eq emissions account for 14%, arising from one plot with LUC related emissions of 10 kg CO_2-eq per kg cocoa. No LUC related emissions occurred in Yamasa. CO_2-eq emissions from transportation are lowest in Medina with 0.15 kg (47% of total GWP), followed by Yamasa with 0.20 kg (67% of total GWP) and Navarrete with 0.25 kg (6% of total GWP). The differences in absolute transport emissions are the varying transportation distances. Since all cocoa is packaged in containers for overseas in Medina, distances are highest for cocoa from Navarrete (251 km), followed by cocoa from Yamasa (149 km) and lowest for cocoa from Medina with a transport distance of 84 km from the processing centre to the port in Santo Domingo. Within transportation, overseas transportation by ship has the largest emissions with 0.07 kg CO_2-eq emissions. Transportation on site with tractor or forklift has a share between 8% (Navarrete) to 13% (Medina) within transportation. Mules and horses have the lowest share within transportation between 5% (Yamasa) and 7% (Medina, Navarrete) through methane emissions from enteric fermentation. Even though only a small share is additionally dried with a gas oven, the relative share from gas drying is 17% for cocoa from Yamasa

(0.05 kg CO_2-eq), respectively 23% from Medina (0.07 kg CO_2-eq), seen in Figure 26. Gas drying in Yamasa is 2.2 times as GHG intense compared to post-drying cocoa in Navarrete, where pre-dried cocoa is transported to Navarrete to dry and being transported to Medina for the further processing. Compared to standard tunnel drying in Yamasa, Gas drying in Yamasa is 18 times as GHG intense compared to tunnel drying. Calculations can be found in the supplementary material (Figure 24).

Emissions from the production of polyethylene bags have a share of 9% for cocoa from Yamasa, respectively 10% from Medina and 0.5% for cocoa from Navarrete. Other materials only have a share of less than 1% in Navarrete and 4% in Medina and Yamasa. Figure 5 shows that the average weighted GWP of 2.80 kg CO_2-eq is dominated by Land use change driven CO_2-emissions from the mentioned 4 LUC-intense plots in Navarrete (89%).

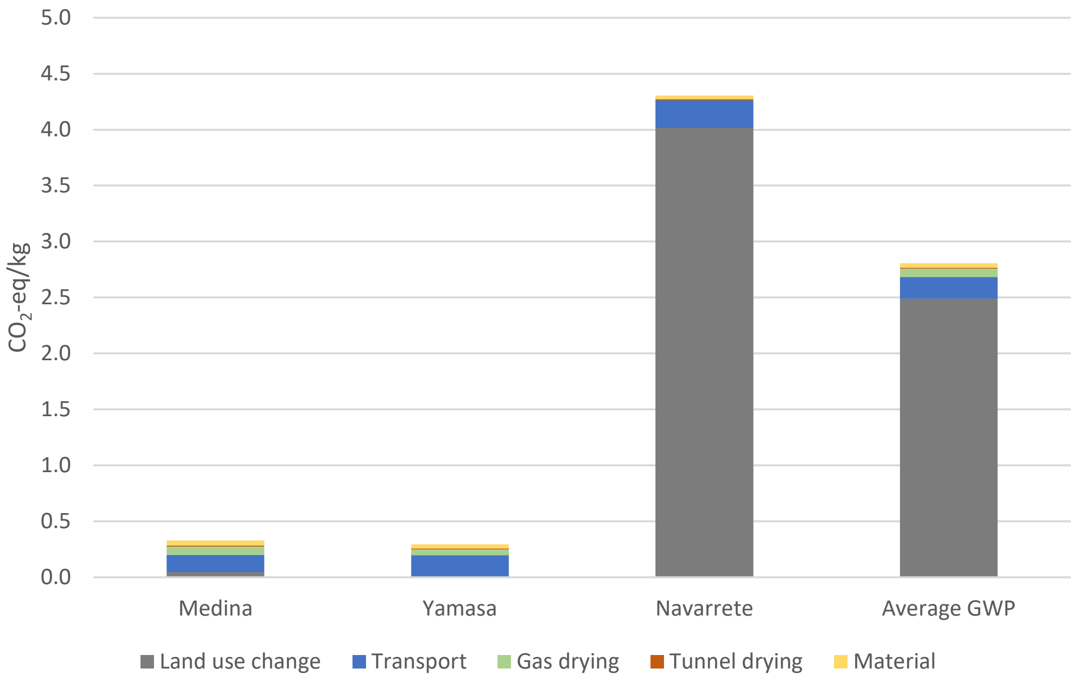

Figure 5 Overall weighted average global warming potential of dried organic cocoa from the Dominican Republic (LUC 20y), and average GWP for the regions Medina (N= 17), Yamasa (N=12) and Navarrete (N=18), according to IPCC (2021).

Average yields of dry cocoa are 360 kg/ha in Medina, 432 kg/ha in Navarrete and 518 kg/ha in Yamasa with values between 89 kg and 750 kg/ha. GWP for specific plantations varies between -1.3 kg CO_2-eq to 52.3 kg CO_2-eq, depicted in Figure 6. Both results, positive and negative, are dominated by land use change related emissions. A total of 5 plots has LUC related emissions due to the conversion of native forest. A total of 6 plots has a net carbon accumulation due to the land transformation from annual cropland, perennial cropland, and grassland. Nevertheless, weighted emissions exceed accumulations by far, resulting in net emissions of 2 t CO_2-eq per hectare, as displayed in Figure 12.

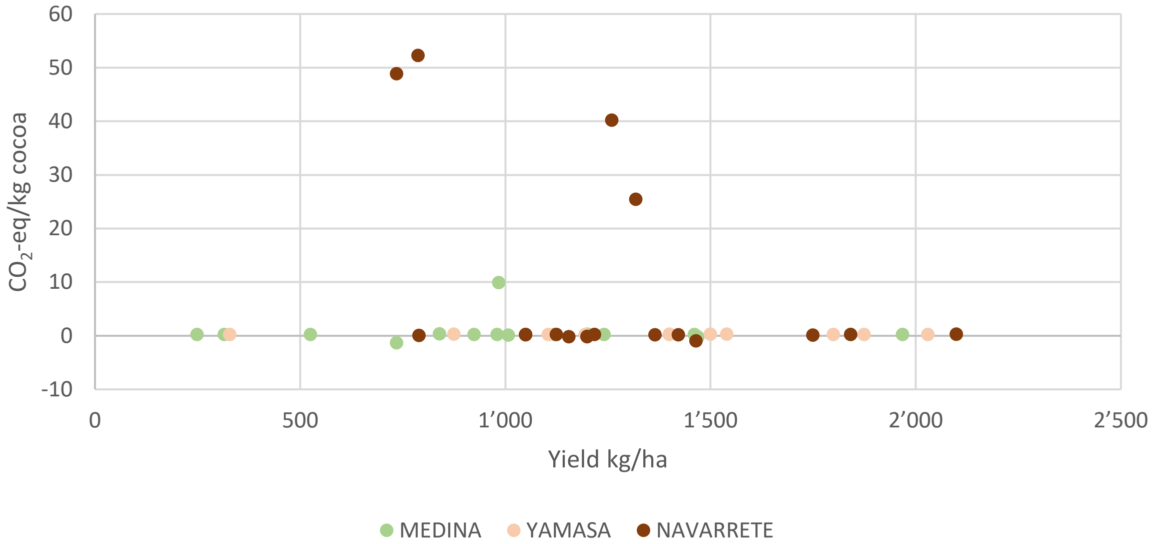

Figure 6 GWP of 1 kg dried organic cocoa from the Dominican Republic in relation to the yield (kg/ha) for 47 producers. The results are coloured differently according to the 3 regions Medina (=light red), Yamasa (=orange) and Navarrete (=dark red).

4.2 TOTAL ENVIRONMENTAL IMPACT – ECOLOGICAL SCARCITY (2021)

The total environmental impact for 1 kg dried organic cocoa from the Dominican Republic is of 307'000 ecopoints, illustrated in Figure 7 and Figure 8**.** As a comparison, the total environmental impact per year caused by average consumption per person in Switzerland in 2018 was 26 million ecopoints (Nathani et al., 2022). The most contributing process is land occupation with a share of 99%, where the most relevant impact category is land use (biodiversity), followed by global warming. Impact category land use (biodiversity) is based on the characterisation factors of the method land use biodiversity from Chaudhary & Brooks (2018) and is applied separately in more detail in chapter 4.3. Global warming causes a total of 2'810 ecopoints. Land use change related CO_2-eq emissions account for 89% of the impact category Global warming. 2.6% (72 EP) are caused from sea freight transportation, 1.3% by the burning of propane from the drying oven.

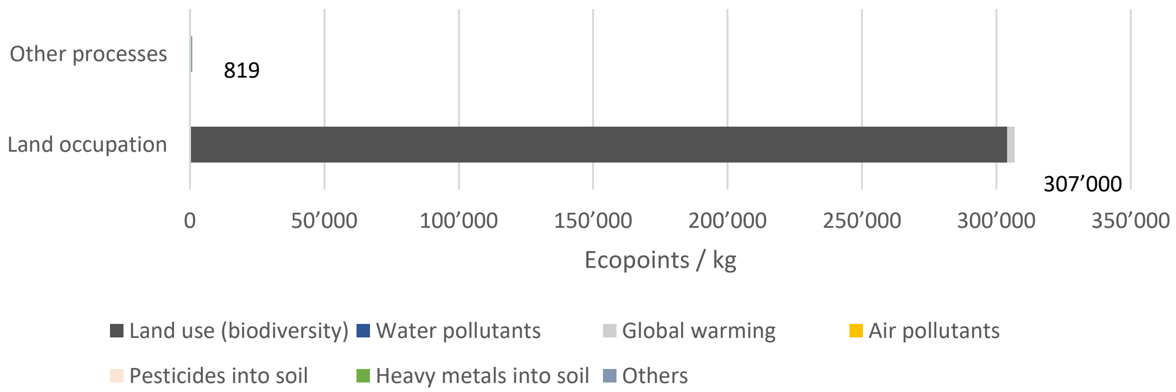

Figure 7 Total environmental impact per kg of dried organic cocoa from the Dominican Republic., expressed in ecopoints according to the ecological scarcity method (Frischknecht et al., 2021). The bars represent ecopoints from Land occupation and other processes (Transport, Material & machines, Gas drying and Pesticides).

For a better visualisation, all remaining processes next to land occupation are depicted separately: Figure 8. illustrates the total environmental impact for the categories transportation, materials & machines, gas drying and pesticides with a total of 819 ecopoints, resulting in a share of 1%, displayed in Figure 7 as “others”. Transportation causes a total of 452 ecopoints. The impact categories Global warming and Air pollution have the biggest share for the process transportation due to the burning of fossil fuels from combustions. Material & machines cause a total of 304 ecopoints. The summarised impact categories *Others* have the biggest share, deriving from non-radioactive waste. A total of 46 ecopoints derive from the drying of the beans with a propane burning gas oven. 80% or 36 ecopoints are caused by the burning of the propane gas. 54% (76 ecopoints) of all air pollutants are caused by nitrogen oxides and sulfur dioxides. Nitrate, phosphorus, and phosphates from feed production of the horses and mules as well as the contamination with pesticides are the biggest source of the category water pollutants. 93% of all pesticides into soil derive from food production for the horses and mules (see Table 19). Only 3% arise from the contamination of the herbicide 2,4-D.

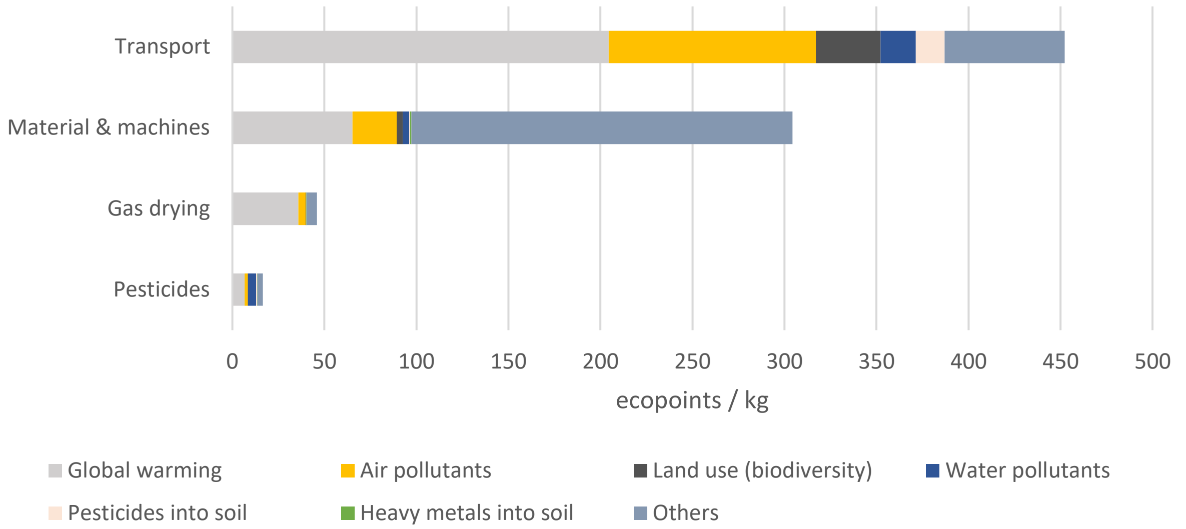

Figure 8 Total environmental impact per kg dried organic cocoa from the Dominican Republic, expressed in ecopoints for the categories Transport, Materials & machines, Gas drying and Pesticides according to the ecological scarcity method (Frischknecht et al., 2021). The bars represent ecopoints from all inputs along the life cycle. Note: For improved visualization the total environmental impact, Land use change is not shown in this graph (307’000 ecopoints).

4.3 LAND USE BIODIVERSITY

As illustrated in Figure 9, 1 kg of dried organic cocoa from the Dominican Republic (DR) relates to a total potential global loss of 4.98E-08 species. Mostly affected is taxa plants with a share of 82% (PSL 4.11E-08), followed by taxa amphibians with a share of 14% (PSL 6.83E-09). Taxa birds, mammals and reptiles have an individual share of less than 3% (PSL 2.39E-09, 3.34E-10 and 2.79E-10, respectively). The results are based on the characterisation factors of the ecoregion Hispaniolan moist forests. The calculations are based on the directly occupied are of the cocoa plantations. Other land use along the process such as land occupation of infrastructure such as drying tunnel or land occupation from feed production of mules and horses is not included. The influence of these processes is considered to only have minor impact since direct land occupation from cocoa cultivation contributes more than 99% of all land occupation. Since the implemented method in SimaPro does only contain characterisation factors on country level, calculations were done manually with the provided characterisation factors from the authors of the method[9]. Characterisation factors can be found in the supplementary material (Table 8).

[9] A. Chaudhary, personal communication, 25 June 2023

The global land occupation related potential disappeared fraction of species for 1 kg of dried organic cocoa is 3.67E-13 (Figure 25). Further elaboration on the potential damaged fraction (PDF) will be done in chapter 5.3.

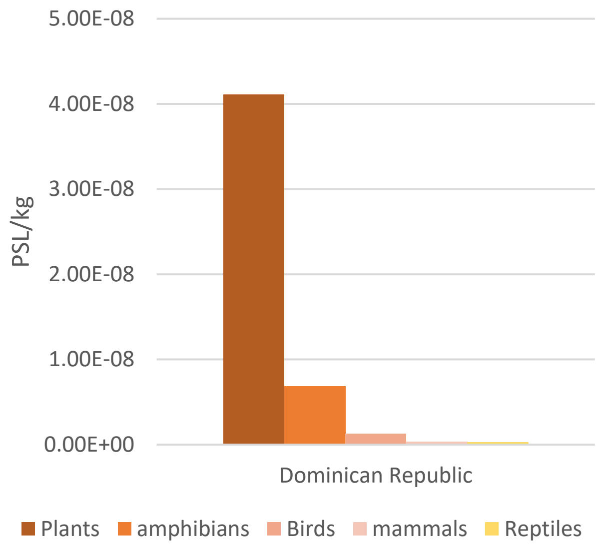

Figure 9 Land occupation related global potential species loss (PSL) of 1 kg dried organic cocoa from the Dominican Republic for the ecoregion Hispaniolan moist forests, for 5 taxa Plants, Amphibians, Birds, Reptiles and Mammals. Total PSL is 4.98E-08, assessed with the method from (Chaudhary & Brooks, 2018). The ecoregion characterisation factor was obtained by matching the GPS-data from the cultivation fields with the terrestrial ecoregions map of WWF.

5 DISCUSSION

Looking at greenhouse gas emissions, 1 kg of dried organic cocoa leads to average CO_2-eq of 2.8 kg, with large regional differences. The region Yamasa has the lowest average emissions with 0.3 kg CO_2-eq, followed by Medina with 0.33 kg CO_2-eq (+10%). Cocoa from the Region Navarrete has the highest emissions with 4.3 kg CO_2-eq. The decisive factor for the average GWP is land use change in the period under consideration. The transformation of virgin forest into cocoa plantations leads to high emissions. Transport accounts for 7% of average emissions, while materials and gas drying account for 3 and 2%, respectively. Land use change related GHG emissions have a share of 89%. Transport, gas drying, and materials only have a relevant share if no land transformation emissions occur.

The total environmental impact for 1 kg of dried organic cocoa from the Dominican Republic leads to 307'000 ecopoints. The result is dominated by the impact category land use biodiversity (99%), caused by land use. 89% of the occurring GHG emissions are caused by land use change.

The Dominican Republic has a high biodiversity with many threatened and endemic species. The decisive factor is the taxa plants with a high proportion of plants that occur exclusively on the island. Consequently, characterisation factors are high compared to other countries, leading to high potential species loss. 1 kg of dried organic cocoa from the Dominican Republic leads to a possible global species loss of 4.98E-08. Taxa plants is responsible for 82% of the PSL, followed by taxa amphibians with 14%. Taxa birds, mammals and reptiles have a share of 3% or less.

5.1 DATA QUALITY AND UNCERTAINTIES

The data used for this LCA are of good quality. Core data on the supply chain, production volumes, processes and the regions were delivered by Pronatec or collected on site during data collection. Site-specific data was received during personal exchange with site managers and employees from Yacao and FUNDOPO. However, there are uncertainties or lack of verification of the data. Information on producer data was based on interviews conducted with a standardized questionnaire. Core information such as field size or the income share of side-crops could not be verified by a third party. A measurement of the fields by Pronatec and its comparison with existing deforestation data is in progress to obtain reliable data[10]. For this study in particular, the correct size of the fields is essential as it has an impact on productivity. Furthermore, it is directly linked to emissions from land transformation and biodiversity impact. The results of this study are a momentary reflection and refer to the year 2021. Many of the factors surveyed, such as cocoa yields, yields of secondary crops or market prices, are subject to fluctuations, which may affect the allocation and ultimately the results. In order to demonstrate the influence of the allocation, a scenario with different values was carried out.

Information about land transformation is a crucial factor since it has a share of 89% of total GWP. As stated in Figure 6, Individual fields with high emissions strongly influence the result. Yet this information is based on producer statements and is therefore subject to uncertainty. A first attempt to verify the statements from the assessed interviews about land use change was to compare tree cover gains and losses over the last 20 years with GIS-data from Global Forest Watch (GFW, 2023). Statements could not be verified due to missing coordinates of the fields. Furthermore, GPS-data were taken at the location where interviews took place. These locations do not necessarily correspond to the locations of the fields. Measurements of the fields are being carried out but were not completed before the end of this study. To calculate emissions over a longer time frame, land transformation was measured over 50 years in a scenario. The second uncertainty concerning land transformation are the different land use types. There was no suitable land use type for land called "*terreno blanco*" in local terms. Terreno blanco can be defined as unproductive land with potential to agriculture or other

[10] *N. Merky, personal communication, 15 & 22 June 2023, Pronatec AG*

economic use. Its appearance varies from clear cut areas to shrubland with few small to medium-sized trees[11]. Due to a lack of information, a conservative approach was chosen for this land type with CO_2-eq/ha*y of 0. Therefore, neither positive nor negative effects on CO_2-eq emissions can be displayed due to land use change of the mentioned land type. All emissions were calculated using weighted values over the last 20 years. Details on the total affected land types and their respective emissions can be found in Table 5.

Certain estimations for infrastructure are based on visual inspections and similar existing ecoinvent datasets. Distances were estimated with GPS-data. Nevertheless, such uncertainties are expected to not have significant influence on the results because of their respective small share on the environmental impact. Fuel consumption for the forklifts was estimated since no measurements were done for the average consumption, including consumption during low season. Certain distances from the producers to the intermediaries or from the intermediaries to the processing centre had to be estimated, because GPS data were taken at the site where the interviews took place, which does not necessarily correspond to the producer location.

5.2 SENSITIVITY ANALYSIS

In the following chapter, 3 different sensitivity analyses were carried out to test the robustness of the results and to investigate differences in the results if certain factors change. Land use change related CO_2-eq emissions represent the most relevant parameter with a share of 90% of total GWP (see Global warming potential). Both the assigned allocation factor and the applied time frame of 20 years for CO_2 due to direct land use change highly influent the GWP and have a high uncertainty level. Therefore, different allocation factors and a different time frame for land use change were applied. The third analysis is a Monte Carlo Analysis, assessing the uncertainty of the data used. For this purpose, the standard deviation of each inventory entry is defined and recorded in SimaPro.

Different allocation factors: Uncertainties regarding the allocation factor of 53% occur on different aspects: Firstly, yields were estimated by the producers over 2 following years. Secondly, certainly not all crops are sold at market prices. Thirdly, market prices are too subject to fluctuation. Data collection showed that cocoa is the main income or only income for 92% of the interviewed producers. Cocoa was a secondary income for only 8% of the producers. Under these assumptions, the allocation factor for cocoa is rather low and a higher allocation factor can be considered as realistic. Therefore, 2 scenarios were calculated with an allocation factor of 75% and 100%. Figure 10 illustrates the GWP of 1kg of dried organic cocoa from the Dominican Republic for allocation factors 53%, 75% and 100%. Increasing the allocation factor to 75% results in a 36% higher GWP of 3.82 kg, compared to the average allocation. An allocation factor of 100% results in a GWP of 5.0 kg (+78%).

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[11] José (last name unknown), personal communication, 02 March 2023, Fundopo

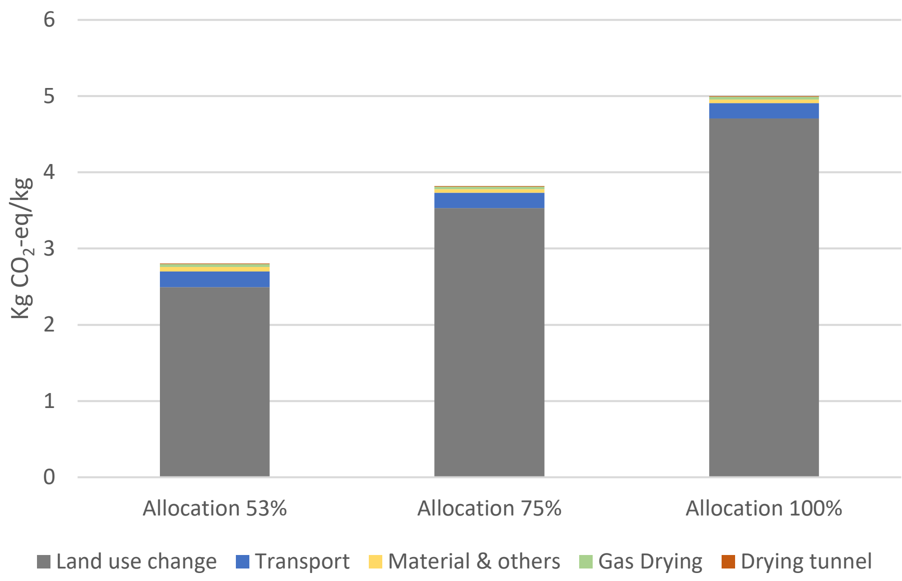

Figure 10 Global warming potential of the analysed average dried cocoa in the Dominican Republic with different applied allocation factors, in kg CO_2-eq according to IPCC (2021).

Figure 11 illustrates the Global Potential Species Loss of 1 kg of dried organic cocoa from the Dominican Republic for allocation factors 53%, 75% and 100%. Increasing the allocation factor to 75% results in 42% higher PSL of 4.72E-10. An allocation factor of 100% results in 89% higher PSL of 6.30E-10. Since the allocation factor is linked to the land occupation, an increasement of the allocation factor leads to a linear increase of PSL.

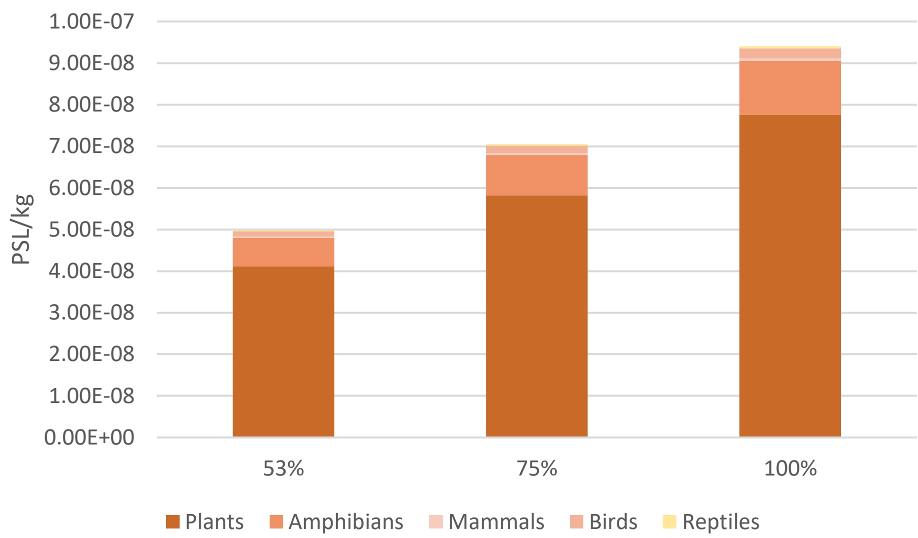

Figure 11 Potential Species Loss of the analysed dried cocoa in the Dominican Republic with allocation factors 53%, 75% and 100%. PSL are calculated according to Chaudhary & Brooks, 2018.

Land use change 50 years: An amortisation of the impacts of land use change over a period of 20 years after transformation is recommended by the UNEP-SETAC guidelines (Koellner et al., 2013). This time frame is a compromise between different allocation time periods. A shorter time, such as 1 year, would lead to high impacts only for a short period of time. Koellner et al. state that a longer time frame such as 100 years would be a risk of not including the impacts in calculations (2013). To see the influence of time frame on the results, a period of 50 years is chosen. Therefore, a higher land area tends to be impacted by land use change but is amortised over a longer period. Table 5 gives an overview of the affected land use type and emissions for both time frames 20 years and 50 years. Land types and their designation in for the calculations of the emissions in the BLONK-tool can be found in the annex in Table 7.

Table 5 Overview of CO_2-eq emissions from land use change, using both 20 year and 50-year time frames. Positive CO_2-eq mean a release of CO_2-eq into the atmosphere, negative values mean an accumulation of Carbon in aboveground biomass and soil. Emissions per hectare are higher for a time frame of 20 years since their respective amortisation is over a shorter time period. Absolute emissions are higher for a time frame of 50 years since more land is affected.

Previous land use type	**20 year time frame**			**50 year time frame**		
	t CO_2-eq/ha*y	Affected area (ha)	t CO_2-eq	t CO_2-eq/ha*y	Affected area (ha)	t CO_2-eq
Annual cropland	-4.93	0	0.00	-1.97	29	-56.92
Perennial cropland	-0.26	113	-29.26	-0.10	220	-22.93
Tropical Rain forest	22.36	53	1'186	8.94	139	1241
Shrub land (terreno blanco)	0.00	37	0.00	0.00	44	0
Tropical moist & wet grassland	-1.51	40	-59.82	-0.60	43	-26.21
Total		242	1'097		475	1'135
Total t CO_2e/ha*y (548 ha)			2.00			2.07

44% of the total area under investigation was transformed within the last 20 years. 19% was converted from coffee plantations or other perennial crops, 113 hectares (21%) were converted from native forest, leading to total emissions of 1'186 tons CO_2-eq. and 7% each from terreno blanco and pasture fields. There was no conversion of annual cropland (e.g. sugar cane). Most of the cultivation area (87%) was converted within the last 50 years. 139 out of a total 548 hectares (25%) were converted from tropical rainforest, leading to total emissions of 1'241 tons CO_2-eq. 40% was converted from perennial cropland. The conversion of 43 ha of grassland led to an accumulation of 26 tons CO_2-eq.

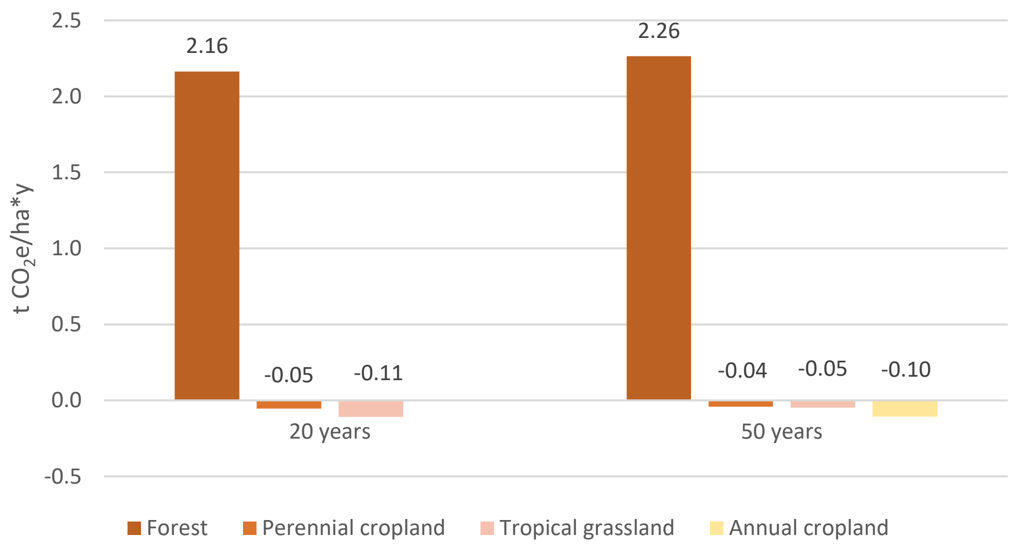

Figure 12 Weighted average land use change related CO_2-eq emissions per hectare land use to produce cocoa in the Dominican Republic for the study subject over both, a time frame of 20 years and 50 years. The conversion from tropical rain forest to cocoa agroforestry systems leads to CO_2-eq emissions. The conversion from annual and perennial cropland as well as tropical grassland leads to a storage of carbon.

Figure 12 shows a comparison of land use change related CO_2-eq emissions for 1 hectare of cocoa plantation for the study subject for a timeframe of 20 years and 50 years. Total emissions per hectare differ only little. For a timeframe of 20 years, 2 t CO_2-eq are emitted, only 4% less than for a timeframe of 50 years (2.07t). Emissions are dominated by the conversion of tropical rain forest to cocoa plantations, resulting in emissions of 2.16 tons/ha*y for 20 years, respectively 2.26 tons/ha*y for 50 years. The conversion of perennial cropland (e.g. coffee) leads to net accumulations of 0.05 t CO_2-eq/ha*y, the conversion of tropical moist & wet grassland to net accumulations of 0.1 t CO_2-eq/ha*y. For the cultivation areas under study, there has not been any conversion from annual cropland within the past 20 years. But it leads to an accumulation of 0.1 t CO_2-eq for a timeframe of 50 years.

Even though forest only accounts for 22% of the total converted area within 20 years and 29% within 50 years, it is responsible for all occurring emissions. The accumulations from annual and perennial cropland as well as grassland only lower the net emissions to a limited extent.

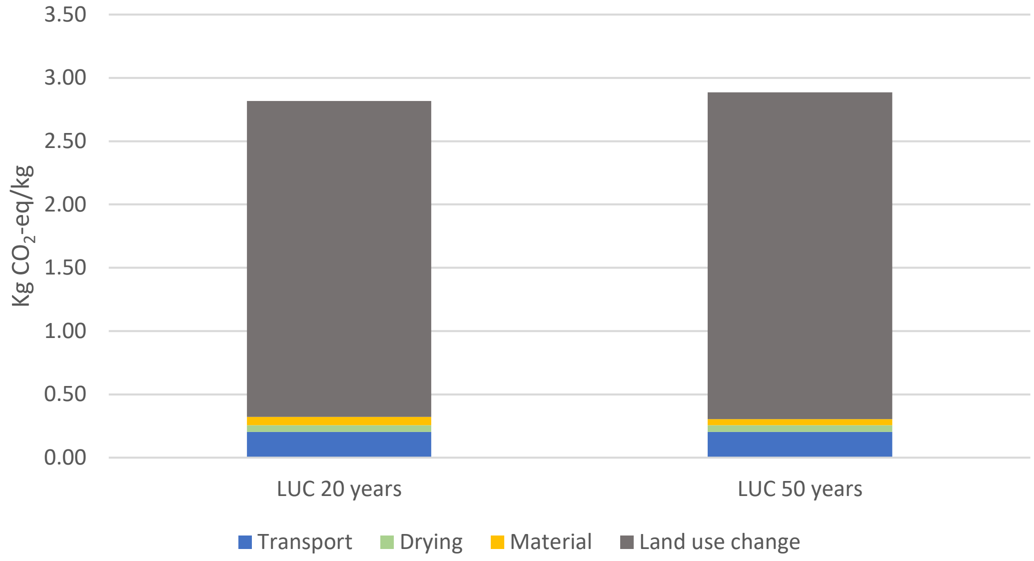

Figure 13 GWP comparison of dried cocoa with land use change related CO_2-emissions with a time frame of 20 years and 50 years, divided into 4 processes Transport, Drying, Material and Land use change.

The result, depicted in Figure 13, shows that even though a higher share of area is affected by land transformation (+96%), the resulting increasing emissions per hectare and year, are minimal. Compared to a considered period of 20 years, GWP with a considered period of 50 years is 2.88 kg CO_2-eq and just 3% higher.

Overall Uncertainty Analysis (Monte Carlo-Simulation): To address the overall uncertainties arising for all inventory data, a Monte Carlo analysis was carried out. It is a way to run a high number of assessments, using random input values for each life cycle inventory entry from a specified probable range guided by probability statistical theory. For all values, standard deviation and uncertainties were added. The uncertainties in the various data inputs add up and can heavily influence the results in both directions. A total of 10’000 Monte Carlo runs with an uncertainty interval of 95% were calculated to map an uncertainty distribution. The evaluation results in a mean GWP of 3.1 kg CO_2-eq with a median GWP value of 1.04 kg CO_2-eq and a standard deviation (SD) of 9.07 kg. The 95% confidence interval is between 0.239 kg and 18.1 kg. This means that 95% of the results are within this range. The analysis confirms the findings that the results are determined by a few outliers with high emissions.

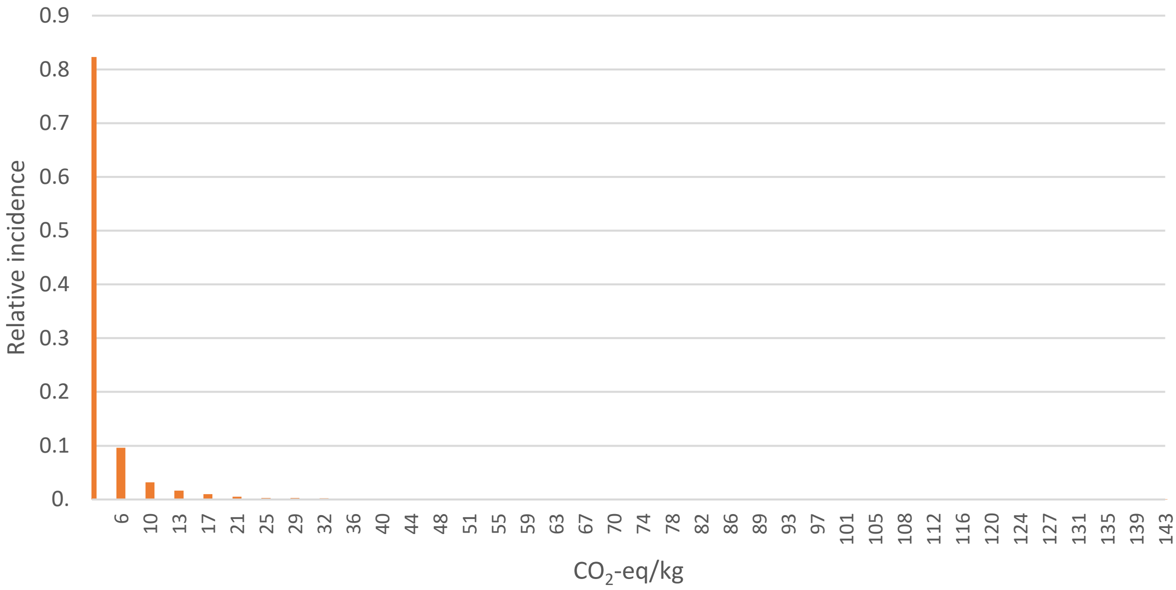

Figure 14 Monte Carlo uncertainty analysis for the environmental impact of 1 kg dried organic cocoa from the Dominican Republic for GWP according to IPCC (2021). With a total of 10'000 runs and a confidence interval of 95%. Standard deviations for specific processes were either calculated manually or calculated with SimaPro.

5.3 COMPARISON WITH LITERATURE

To put the results of this study more into context, a comparison with literature was done with FAO-data and other LCA studies to identify country-specific similarities and differences. First, yields are compared, followed by a comparison of the results for the three executed impact assessment methods.

Yield: Within this study, there is a large variation between the collected data. Field size vary from less than 1 hectare to 88 hectares (Figure 21) with yields from 89 to 750 kg/ha*y with a median yield of 428 kg per hectare. This is in the middle range from the compared yields for agroforestry systems (Table 12) but lower than the country average of 527 kg/ha*y, stated by FAO (2023). Certain studies that have examined cocoa from Latin American countries, state yields below 300 kg/ha (136-280 kg/ha) for pure and mixed agroforestry systems (Deheuvels et al., 2012; Froborg, 2022; Gockowski & Sonwa, 2011; Roth et al., 2020). Lazzarini et al. (2022) also mention a wide range of yields in the existing literature for organic cocoa, with values between 100 and 1'000 kg per hectare with many influencing factors such as irrigation, application of fertilizers and pesticides, age of the trees, cocoa variety, or different farm management.

GWP: Available studies report emissions between 0.32 kg CO_2-eq to 40.9 kg CO_2-eq. Many results are not directly comparable with this study since they did not include land use change which turned out to be a decisive factor in this study. In studies where land use change has been included, WGP results range from 1.47 kg CO_2-eq to 40.9 kg CO_2-eq and make up a great share of total GWP. The GWP of Colombian cocoa from the study of Ortiz-Rodriguez et al (2016) is 8.89 kg, where the emissions of anaerobic decomposition of the pod husks have a share of 85%. Due to the broad distribution of the husks in the fields, it is assumed that no anaerobic decomposition occurs for this study. The average GWP value of 2.80 kg CO_2-eq emitted per kilogram dried cocoa beans from this study falls in the lower range found in other LCAs. Average CO_2-eq emissions for both regions Yamasa (0.30 kg CO_2-eq) and Medina (0.33 kg CO_2-eq) are on the lower range of GWP, comparable with the results of Ntiamoah & Afrane (2008) and Pérez-Neira et al. (2020) whose results range between 0.32 and 0.61 kg CO_2-eq.

Whenever land use change was included in the LCAs, it is the decisive factor of GWP. Parra-Paitan & Verburg (2022) conducted an LCA for Ghanaian cocoa at farm level. They state that carbon emissions from land use change in cocoa full-sun systems were 18% lower compared to agroforestry systems due to higher yield, resulting in lower land demand. The performance of organic agroforestry systems from Pérez-Neira et al. was even better. The GWP was 56% lower compared to conventional monoculture systems (2020). To define the land use change related CO_2-eq emissions, first, the calculation of aboveground, soil and dead matter carbon stock needs to be measured. As stated in chapter 5.2, the carbon stock values of the reference situation and the expanding crop are crucial for a correct calculation of land use change related emissions. A comparison with literature reveals big differences in both aboveground and soil carbon stock. Since no further values for the Dominican Republic exist, comparisons can only be done with values from different countries. Agroforestry systems from 5 South American countries from the study of Somarriba et al. (2013) had an average total carbon stock of 117 (+/-47) t/ha. The differences could be explained by a higher density of big shade trees which generally are able to store more C than cocoa trees. Goñas et al (2022) state that carbon storage capacity is strongly related to tree age and proportion of cocoa trees and timber and shade trees: Older plantations and plantations with a higher ratio of timber and shade trees are able to store more carbon. Values range from 134 t C/ha for young cocoa systems to 175 t C/ha for adult systems in Peru. Compared to the findings of Mohammed et al. (2016), cocoa systems in the Dominican Republic store only between 51% and 99% the amount of carbon than cocoa systems from Ghana (81.8 t – 154 t C/ha). Agroforestry cocoa from southeast Asia had a total carbon storage of 57.4 t C/ha which is significantly less (Rajab et al., 2016). Shade trees contributed between 57 and 78 percent of the total carbon stored. Comparing C storage/ha in native vegetation from different countries (DR = 203 t , PE = 206 t, GH = 226 t, EC = 282 t, ID = 298 t), the Dominican Republic has the lowest C storage with 203 t C/ha (Blonk Consultants, 2021). The comparison reveals that carbon storage in cocoa systems in the Dominican Republic is rather low. It has the lowest range in C storage compared to other major cocoa producing countries. All compared studies have the following in common: Firstly, C storage is higher in agroforestry-systems compared to monoculture systems. Secondly, C storage increases with the proportion of shade trees. Thirdly, C storage is highest in natural and untouched forests (Goñas et al., 2022; Mohammed et al., 2016; Nijmeijer et al., 2019; Rajab et al., 2016; Somarriba et al., 2013).

The application of inorganic fertilizers and pesticides and fertilizers can have a relevant share on GWP. For cocoa from the Ivory Coast, the application of inorganic nitrogen fertilizer has a share of 8.75% (ecoinvent dataset *Cocoa bean {CI}| cocoa bean production, sun-dried | Cut-off, U*). Higher shares were observed by Pérez-Neira et al. (2020), as the application of fertilizers was responsible for 31% of the emissions. Another relevant factor could be artificial irrigation of the fields. It is responsible for 11% of GWP for cocoa from the Ivory Coast (ecoinvent dataset *Cocoa bean {CI}| cocoa bean production, sun-dried | Cut-off, U*), arising from the burning of diesel and emissions from the production of electricity of electric pumps. In the study of Pérez-Neira et al. (2020), transportation could have a relative share between 9 and 51% of total GWP. For the average cocoa from this study, the relative share of transportation is slightly below this range with 7%. However, for transportation has the highest relative share for the regional average in Yamasa and Medina with 47% and 67% respectively.

Total environmental impact – ecological scarcity (2021): To draw a comparison with cocoa from other countries, an evaluation was made with existing ecoinvent datasets for 1 kg of cocoa (see Table 20). Figure 15 shows the total environmental impact with the method ecological scarcity (2021) for cocoa from Indonesia, Ghana, and Ivory Coast. Cocoa from the Dominican Republic has by far the highest total environmental impact with a total of 307'000 ecopoints. Cocoa from Indonesia has a 16% lower total impact, followed by Ghana (-71%) and the Ivory coast (-75%). The decisive factor for the large differences is land use, which makes up 99% for cocoa from the DR but only between 62% and 64% for ID, GH and CI.

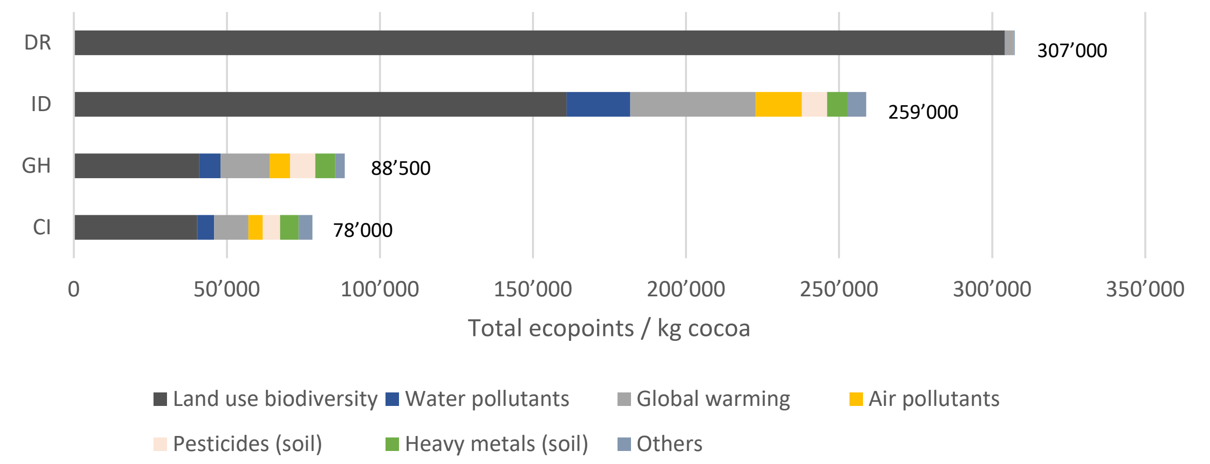

Figure 15 Comparison of the total environmental impact of 1 kg dried cocoa from the Dominican Republic with dried cocoa from Indonesia, Ghana, and Ivory Coast, according to ecological scarcity (2021). Subdivided into contributions of Land use biodiversity, Water pollutants, Global warming, Air pollutants, Pesticides, Heavy metals, and Others. Values for ID, GH and CI were taken from ecoinvent datasets, sea freight transport was added (see Table 20)

Land use biodiversity has a contribution between 46 and 99%, displayed in Figure 15. Values are based on the country specific occupation characterisation factors from Chaudhary & Brooks (2018). Global warming has a contribution between 1 and 18%. Water pollutants and air pollutants and Heavy metals all have a share between 0 and 8%. Pesticides have a contribution between 0 and 9%. Other categories such as radioactive substances, non-radioactive waste or other pollutants are summarised as “*others*” with a contribution between 0 and 6%. The analysis shows that except for Land use biodiversity and Global warming, other impact categories do not have a relevant share on the total environmental impact for Dominican cocoa. High characterisation factors and a rather low yield are responsible for high contributions of land use biodiversity for cocoa from the Dominican Republic and Indonesia. In absolute numbers, GHG from cocoa from Indonesia has a total contribution of 41’000 ecopoints, which is a factor 14 higher compared with cocoa from the Dominican Republic (3’000 ecopoints).

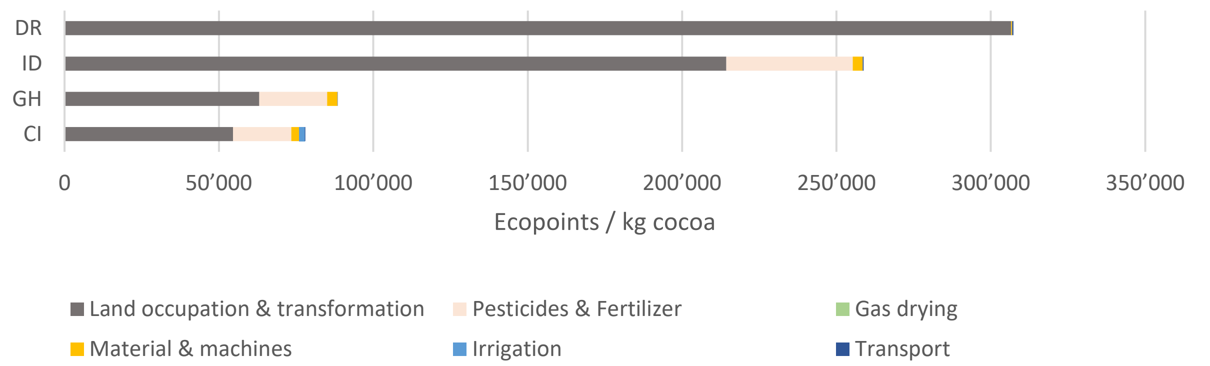

Figure 16 Comparison of the total environmental impact of 1 kg dried organic cocoa from the Dominican Republic with dried cocoa from Indonesia, Ghana and Ivory Coast, according to ecological scarcity (2021). Subdivided into the process steps along the life cycle, namely Land occupation & transformation (dark blue colour), Pesticides & Fertilizer (red colour), Gas Drying (grey colour), Materials & machines (yellow colour), Irrigation (light blue colour) and Transport (green colour).

The observation of the different process steps reveals that the processes land use and pesticides are the main contributors of the total environmental impact. Land use (occupation and transformation) has a share of between 70 and 99.7%, depicted in Figure 16. Pesticides & Fertilizers have a share of up to 24.8% (GH). For cocoa from Ghana, Indonesia, and the Ivory Coast, 98 to 99% of the midpoint categories water pollutants and pesticides into soil occur from the application of pesticides. Irrigation does only occur in the Ivory Coast and has a share of 2.4%. 100% (1’600 EP) of the impact category

Water resources is caused by irrigation. Materials & machines have a share of up to 3.7%, due to the impact category *waste (non-radioactive)* from the treatment of waste wood (landfill & open dump). An evaluation at the level of the 3 regions Medina, Yamasa and Navarrete for the impact assessment method total environmental impact was not possible, as these were modelled in MS Excel and not modelled in SimaPro.

The impact category land use biodiversity is based on the method of Chaudhary & Brooks (2018), where the Dominican Republic has the highest characterisation factors per m^2 (see Table 8). Another reason for such high numbers is the yield which is directly linked to land use biodiversity. Cocoa from the Dominican Republic has the lowest yield with 428 kg/ha, followed by cocoa from Ghana (457 kg/ha), Indonesia (493 kg/ha) and Ivory Coast (614 kg/ha). Only cocoa from the Dominican Republic has an allocation factor (53%) which reduces impacts accordingly. Calculating with a higher allocation factor, the total environmental impact of Dominican cocoa would amount to 579’000 ecopoints (+89%), resulting in even greater differences. It should be noted that within the method of Ecological Scarcity, country specific characterisation factors are used for the calculation of the midpoint category land use biodiversity. A comparison between the combined country specific and ecoregion specific characterisation factors reveals big differences. Country-specific aggregated CF in the Dominican Republic, Indonesia and Ghana are higher than the aggregated ecoregion-specific CF with +25%, +91% and +103%, resulting in an overweighting of the impact category land use (biodiversity). Calculating with ecoregion specific CF would lead to more accurate results and lower values for the impact category land use (biodiversity). Country-specific aggregated CF in Bolivia, Peru and Ivory Coast are lower than the aggregated ecoregion-specific CF with -81%, -3% and -46%, resulting in an underweighting of the impact category land use (biodiversity). Calculating with ecoregion specific CF would lead to more accurate results and higher values for the impact category land use (biodiversity). Calculations of the specific characterisation factors can be found in Table 11.

The total environmental impact per person in Switzerland reduced from around 35 million ecopoints in 2000 to 26 million ecopoints in 2018 (Nathani et al., 2022). Based on Switzerland's environmental targets and legal limits, the total environmental impact should be reduced by 67%. The food category as a final demand area has the second largest share after housing, with a share of 25% or roughly over 6 million ecopoints. 60% of the environmental impact from Swiss demand occurs abroad. With a consumption of 11 kg chocolate (Statista, 2023) and an assumed share of 50% cocoa, the possible total environmental impact from cocoa could be as high as 1.67 million ecopoints or 28% of the total environmental impact of the Swiss food. For comparison, the total environmental impact of coffee is between 14’000 (BR) and 88’000 (IN) ecopoints, hence 71 to 95% lower than cocoa. The total environmental impact of 1 kg of apples 4’400 ecopoints (-99%). The mentioned products were calculated with datasets from ecoinvent (1 *Coffee, green bean {ID}| coffee green bean production, robusta | Cut-off, U, 2 Coffee, green bean {BR}| coffee green bean production, robusta | Cut-off, U, 3 Apple {GLO}| market for | Cut-off, U).* To achieve the mentioned reduction of 67%, the environmental impact of cocoa needs to be reduced drastically.

Land use biodiversity: To classify the results of the biodiversity impact of cocoa from the Dominican Republic, a comparison was made with cocoa from 4 other countries, listed below in Table 6. Potential species loss and potential damaged fraction of species loss depends on 3 factors: Characterisation factor, yield (kg/ha) and an allocation factor that determines what share of land is being attributed to the functional unit. An allocation was only applied for cocoa from the Dominican Republic. Productivity varies greatly with the highest yield in Peru, followed by the Ivory Coast, Indonesia, the Dominican Republic, and Bolivia with the lowest yield.

Table 6 Overview the ecoregion and productivity of the DR, PE, BO, CI and ID for the comparison of land use biodiversity impact according to Chaudhary & Brooks (2020). Ecoregions were attained from Olson et al. (2001)

Country	**Allocation factor**	**Ecoregion**	**Land use m^2/kg cocoa**	**Source**
Dominican Republic (DR)	53%	Hispaniolan moist forests	23.3	Current study
Peru (PE)	100%	Ucayali moist forests	11.8	(Pronatec, 2023c)
Bolivia (BO)	100%	Bolivian Yungas	43.5	(Roth et al., 2020)
Ivory Coast (CI)	100%	Eastern Guinean forests	16.4	Ecoinvent dataset: *Cocoa bean {CI}| cocoa bean production, sun-dried | Cut-off, U*
Indonesia (ID)	100%	Borneo lowland rain forests	20.3	Ecoinvent dataset: *Cocoa bean {ID}| cocoa bean production, sun-dried | Cut-off, U*

Figure 17 gives a log-scaled overview of the ecoregion specific characterisation factors for the 5 above listed countries. Taxa plants in the Dominican Republic has by far the highest CF, being at a factor 6 higher than the second highest CF (Amphibians DR). The illustration reveals big differences of CF between both different taxa and different countries. Characterization factors (CF) differ highly among ecoregion and taxa. CFs for the Dominican Republic have the highest taxa value for 4 taxa, compared with CF values for the respective ecoregion in Bolivia, Peru, Indonesia, and Ivory coast. CF in the ecoregion from the Dominican Republic are highest for taxa birds, amphibians, reptiles, and plants and third highest for taxa mammals. It is notable that the CF of taxa plants is at a factor 14 to 53 higher than CF from the other compared ecoregions. It is the decisive factor for the total PSL in the Dominican Republic, with a PSL of 4.11E-08, followed by Amphibians (6.84E-09), birds (1.27E-09), Mammals (3.34E-10) and Reptiles (2.79E-10). Second highest PSL per kg cocoa has Bolivia with a total PSL of 2.42E-08, which is half the amount of the Dominican Republic.

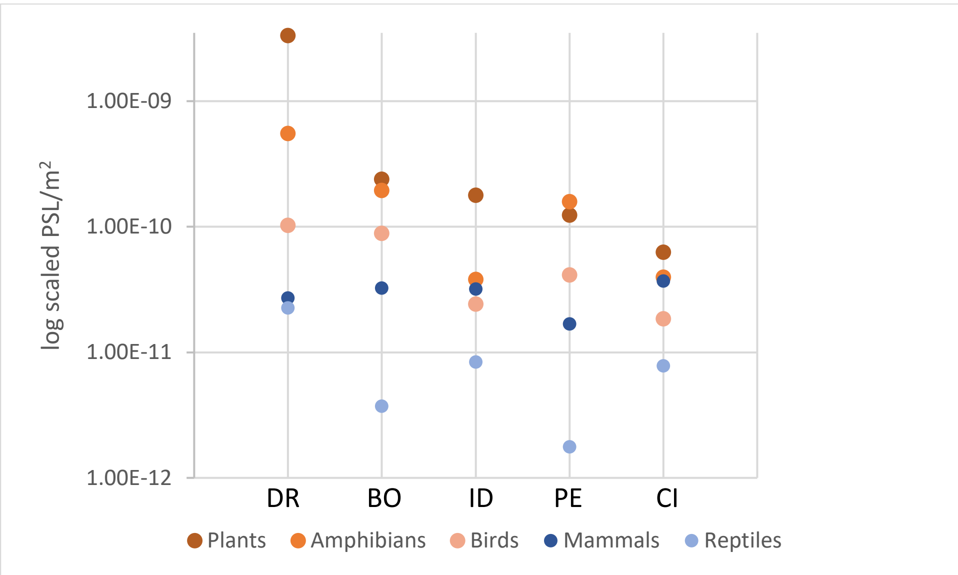

Figure 17 Logarithmic-scaled comparison of the ecoregion specific characterisation factors per m² of cocoa for 5 countries (Bolivia, Dominican Republic, Indonesia, Ivory Coast, Peru) for 5 taxa. The Y axis is logarithmic-scaled.

Figure 18 displays the PSL of 1 kg dried cocoa from the mentioned countries. It should be noted that an allocation factor was only applied to the study object, which significantly reduces the biodiversity impact. With an allocation factor of 100, the PSL and PDF for the Dominican Republic would be significantly higher. To illustrate the influence of an allocation factor, both 53% and 100% allocation factors are displayed. PSL for cocoa from the Dominican Republic with an allocation factor of 100% is highest (9.39E-08) at a factor of 2 to 35. Compared to the Dominican Republic (53%), cocoa cultivation in Bolivia leads to 51% lower possible species loss (2.42E-08), in Indonesia to 89% lower PSL (5.71E-09), in Peru to a 92% PSL (4.02E-09) and in the Ivory Coast to a 95% lower possible species loss (2.70E-09).

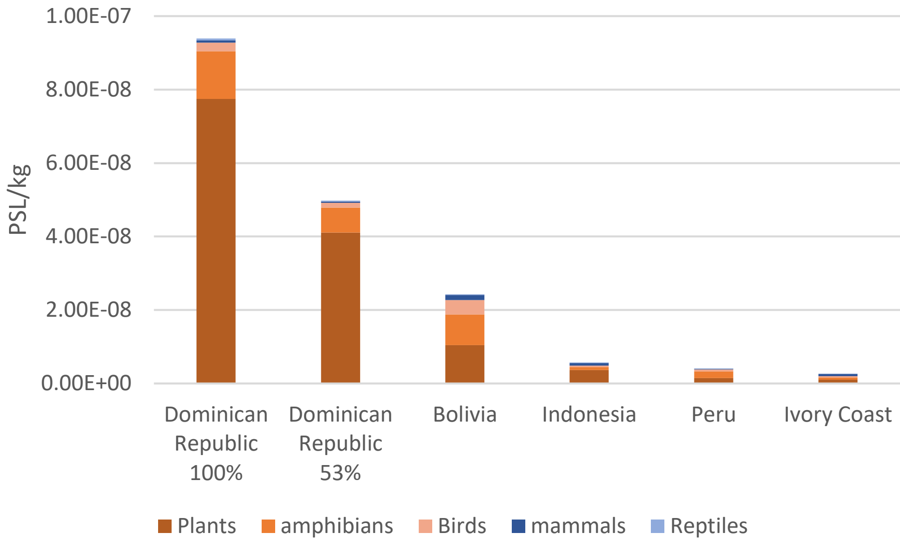

Figure 18 Potential global species loss (PSL) for 1kg dried cocoa from the Dominican Republic 53% allocation, the Dominican Republic 100% allocation, Bolivia, Indonesia, Peru, and the Ivory Coast. PSL was assessed with the Method of (Chaudhary & Brooks, 2018).

The differences can be explained by different characterisation factors and yields. Within the 5 analysed countries the Dominican Republic has the highest characterisation factors for birds, amphibians, reptiles, and plants (See Table 8 in the appendix), deriving from a high share of endemic species and high vulnerability. The biggest difference is the CF for Taxa plants, which is 98% lower for the Ivory Coast. Due to a relatively high abundance of endemic species and a small ecoregion, vulnerability for the Dominican Republic is higher (see method of Chaudhary & Brooks (2018)).Only for taxa mammals, Ivory Coast, Indonesia, and Bolivia have a higher CF. Yields in CI are 43% higher compared to DR, which leads to lower land occupation per kg of cocoa.

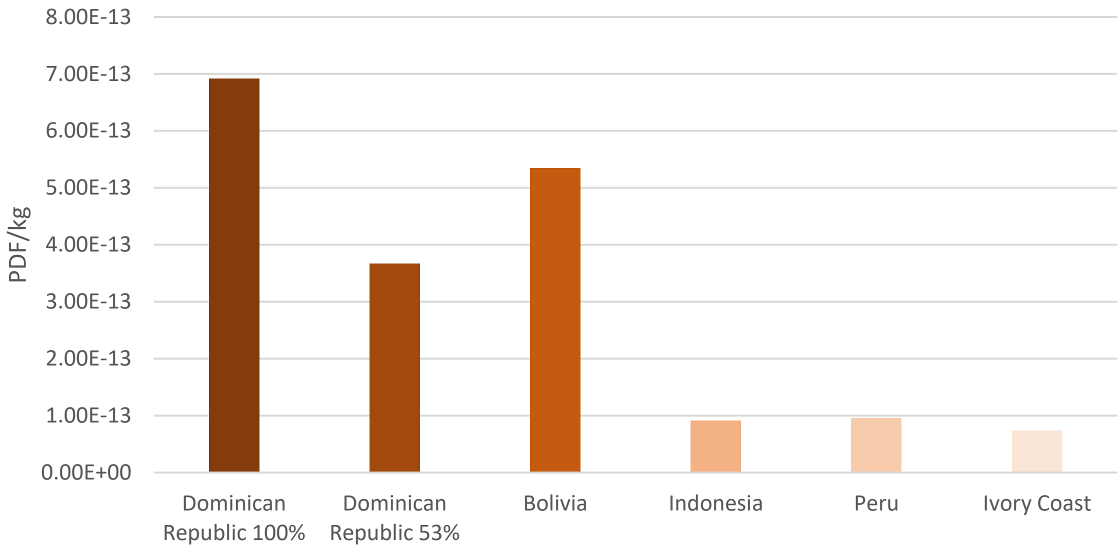

Figure 19 Potential global disappearing fraction of species (PDF) for 1kg of dried cocoa from the Dominican Republic, Bolivia, Indonesia, Peru, and the Ivory Coast. For the Dominican Republic both allocation factors 53% and 100% were applied. PDF was assessed with the Method of Chaudhary & Brooks (2018).

As stated above, an allocation factor was only applied for the Dominican Republic (allocation 53%). To demonstrate the influence of the applied allocation factor, both 53% and 100% allocation were applied, as seen in Figure 19. Assessing the potential global disappearing fraction of species, cocoa from the Dominican Republic with an allocation factor of 100% has the highest value with 6.92E-13. Cocoa from Bolivia has the second highest PDF with 5.34E-13, followed by cocoa from the Dominican Republic (allocation 53%) with a PDF of 3.67E-13. Cocoa from Peru, Indonesia and Ivory Coast have the lowest values with 9.54E-14, 9.14E-14 and 7.34E-14, respectively. The results should be viewed with caution. Due to the different weighting of the taxa for the aggregated PDF characterisation factors, cocoa from Bolivia has a higher PDF than cocoa from the Dominican Republic (53%) but has a lower PSL. It is recommended here by the author of the method to calculate with country-specific CF[12]. Using the country-specific CF would result in a loss of information: With the country-specific factors, no more statements could be made about biodiversity loss at the ecoregion level.

In the study of Parra-Paitan & Verburg (2022) cocoa from Ghana has a PDF of 5.9E-11 for agroforestry cocoa and a PDF of 1.7E-10 for 1 kg full-sun cocoa with yields of 418 and 525 kg/ha, respectively. Eneroth et al (2022) used Chaudhary & brooks method for the production of cocoa powder in the Ivory Coast, Ghana, Ecuador and Nigeria and concluded that organic cocoa has a higher biodiversity impact than conventional cocoa. On average, PDF-values were 27% higher for organic cocoa due to lower yields. Values ranged from 0.86E-11 to 9.3E-11 for conventional cocoa and from 1.1E-11 to 12E-11. The stated values are significantly lower than the calculated values from this study (see Figure 19). In the mentioned studies there was no mentioning of whether ecoregion specific or country specific CF were applied, nor was there any indication what equations for the taxa aggregated PDF-values were taken. Therefore, a direct comparison with the obtained results from this study is not possible. Moberg et al (2020) studied the environmental impact of the Swedish diet and concluded that cocoa had the second highest extinction rate per kg of product, after lamb meat. Cocoa is identified as one of the main drivers of global biodiversity loss (Lenzen et al., 2012).

[12] *A. Chaudhary, personal communication, 25 & 26 June 2023*

5.4 CONCLUSION AND RECOMMENDATIONS

For the coming future, cocoa producers worldwide are faced with serious challenges that need to be addressed now and in the coming years. Warmer temperatures and more erratic rainfall will reduce suitable areas for cocoa cultivation. Many plantations are past their peak production years and the cutting down of forests for new plantations exert further pressure to them (WWF, 2017). With the growing demand for cocoa the pressure on the remaining land and biodiversity is increasing. To reach the aimed reduction of the total environmental impact (-67%) and the biodiversity footprint (-74%) of Switzerland, cocoa plays a central role.

Chaudhary & Brooks method tries to explain biodiversity loss in terms of agricultural land but does not consider factors such as over-fertilisation and eutrophication of water bodies, irrigation with subsequent water scarcity, pollution from machinery and processing and transport. Moreover, taxa such as insects or fish are not considered (Chaudhary & Kastner, 2016). It is recommendable to use a different method that includes these aspects. For example, the ReCiPe 2016 method includes other impact categories such as acidification, eutrophication, ozone formation or global warming (Huijbregts et al., 2016). Due to the sheer complexity of biodiversity and its interrelationships, there are still large gaps in our knowledge.

The results from all 3 conducted impact assessment methods show unmistakeably that land use is the decisive factor of the environmental impact. Even though a net carbon accumulation is possible, the emissions from land transformation, driven by 5 producers with high emissions, outweigh the positive effects and dominate the share of GWP with 89%. Due to high characterisation factors and a rather low yield, Land use biodiversity has a share of 99% of the total environmental impact. Cocoa has a relevant share in the total environmental impact of food in Switzerland. Compared to other countries, the total environmental impact is significantly higher. But, with the potential of increasing yields, biodiversity impact would drop accordingly. The influence of gas drying had not been investigated so far and thus closes a research gap. At regional level, gas drying can have a share of up to 23% of the GWP and is a relevant factor in reducing CO_2-eq emissions. It is up to 18 times more GHG intensive compared to simple solar drying. For regions with only little or no land use change related emissions, transportation is responsible for up to 67% of GHG emissions. Impacts deriving from materials are of subordinate importance with a maximum share of 15% of total GWP.

Based on the outcomes of this study, the following possibilities for improvement were identified to reduce the environmental impact due to the production of 1 kg dried organic cocoa from the Dominican Republic:

Preventing deforestation, supporting reforestation:

- To reduce overall CO_2-eq-emissions it is crucial that an expansion of cocoa cultures does not jeopardize further forested areas, especially not primary forest. The introduction of mechanisms to ensure that no further forest is cleared for the cultivation of new cocoa plantations has the biggest potential on reducing CO_2-emissions.
- Incentivising producers to keep old shade trees. Mature shade trees store significantly more carbon than cocoa trees.
- Planting cocoa on former agricultural land and grassland can sequester carbon and have a positive impact on the carbon footprint.
- A higher diversity of shade trees increases biodiversity.

Maximizing yield:

- Rejuvenate plantations, planting higher-yielding varieties and improved farm management (e.g. pruning) can increase yields and stop an expansion of cocoa plantations into undisturbed areas. Higher yields will reduce land occupation and biodiversity impact will decrease.

Minimizing gas consumption and transport distances:

- Solar drying of cocoa is 94% less GHG intense compared to gas drying. The transportation of cocoa from Yamasa to finish drying in Navarrete is 55% less GHG intense compared to gas drying.

Eliminating the possible residual use of pesticides and herbicides and cross contamination:

- Improved controls and cooperation with neighbouring institutions and producers to stop the use of pesticides and fertilisers in the whole region can reduce emissions and heavy metals into soil and water and therefore reduce the total environmental impact.

In conclusion, this LCA adds to the scarce knowledge regarding the environmental impact of organic cocoa in the Dominican Republic. It revealed a large regional variance of the environmental impact and showed various possibilities to improve the environmental performance through all processes. With the implementation of the above proposed measurements, Pronatec has the potential to reduce the environmental impacts of its cocoa significantly and stand out as an example of sustainable cocoa for the entire cocoa industry.

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Appendix A – Abbreviations

This table gives an overview on all abbreviations used in this study.

Abbreviation	Term
BE	Belgium
BO	Bolivia
C	Carbon
CF	Characterisation Factor
CI	Côte d'Ivoire (Ivory coast)
CO_2-eq	CO_2-equivalents
CP	Conservation Priorities
DR	Dominican Republic
DOP	Dominican Pesos
FU	Functional Unit
GH	Ghana
GHG	Greenhouse Gas
GWP	Global Warming Potential
Ha	Hectare(s)
ID	Indonesia
IPCC	Intergovernmental Panel on Climate Change
LUC	Land use change
MJ	Megajoule
PE	Peru
PSL	Potential species loss
SOC	Soil Organic Carbon

Appendix B – Land use systems

Table 7 Land systems for 1kg dried cocoa within the past 50 years and their description in the BLONK tool (Blonk Consultants, 2021).

Land system before cocoa	Land use according to BLONK	Share (%)
Agriculture	Annual cropland	4.93%
Coffee	Perennial cropland	37.05%
Pasture/grassland	Tropical moist & wet grassland	7.91%
Other perennial crops	Perennial cropland	3.15%
Forest	Tropical rainforest	25.32%
Sugar cane	Annual cropland	0.33%
Abandoned land (terreno blanco)		7.94%
No transformation		13.37%

Appendix C – Age distribution of the interviewed producers

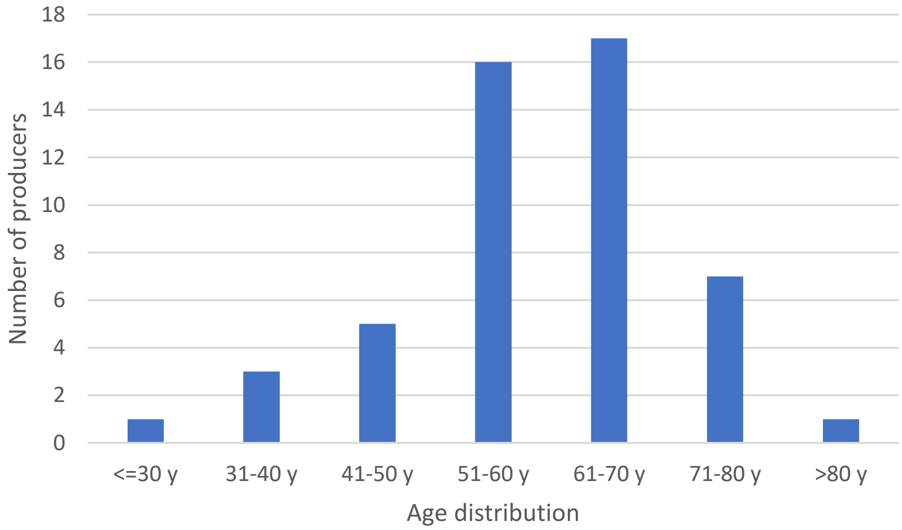


Figure 20 Age distribution of all interviewed producers. Median age = 61 years

Appendix D - Distribution of the field size of the interviewed producers

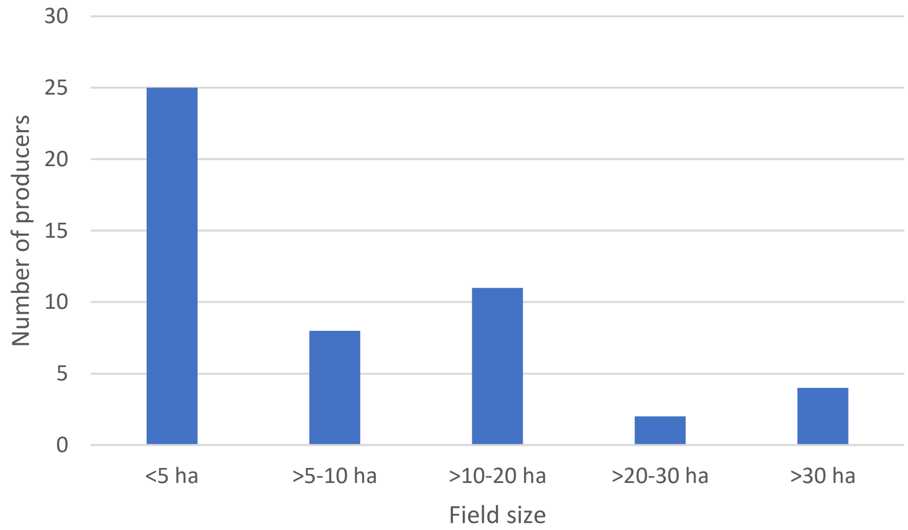


Figure 21 Distribution of the field size of all interviewed producers. Median field size is 4.4 hectares with a maximum of 88 ha and a minimum of 0.6 ha

Appendix E - Comparison of the GWP of different transportation modes

Figure 22 Comparison of the GWP of different transportation modes

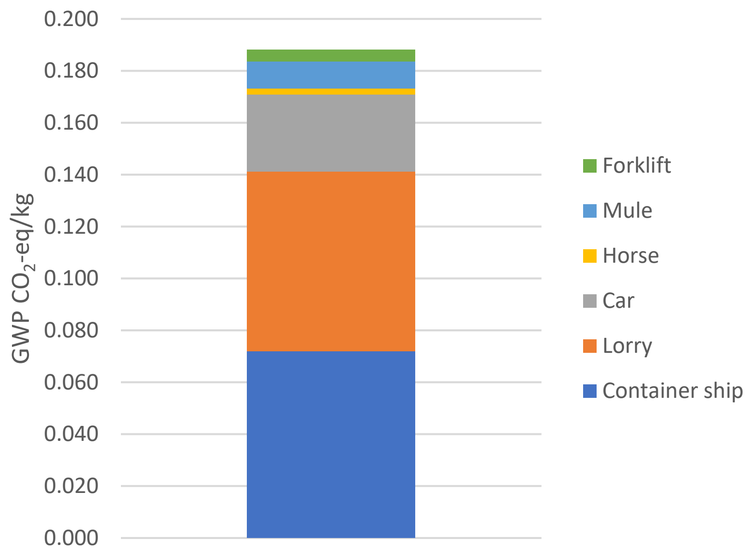


Figure 23 Total CO_2-eq emissions from transportation for 1 kg dried organic cocoa from the Dominican Republic

Appendix F – Comparison of the different drying options

Figure 24 displays the GWP of 4 different drying options. For the transportation, the ecoinvent dataset *Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Cut-off, U* was used. For the drying oven, calculations can be found in Table 18. A propane consumption of 1.061 MJ/kg fermented cocoa was used. The results are based on the following calculations:

1: Yamasa Tunnel drying: Includes the transportation of 65 km from Yamasa to Medina for 1 kg dried cocoa.

2: Navarrete Tunnel drying: Includes the transportation of 167 km from Navarrete to Medina for 1 kg dried cocoa.

3: Navarrete Tunnel re-drying: Includes the transportation of 167 km from of 2.1 kg fermented cocoa from Yamasa to Navarrete and transportation of 167 km from Navarrete to Medina for 1 kg dried cocoa.

4: Yamasa – Gas drying: Includes the drying of 2.1 kg fermented cocoa and the transportation of 1 kg dried cocoa for 65 km from Yamasa to Medina.

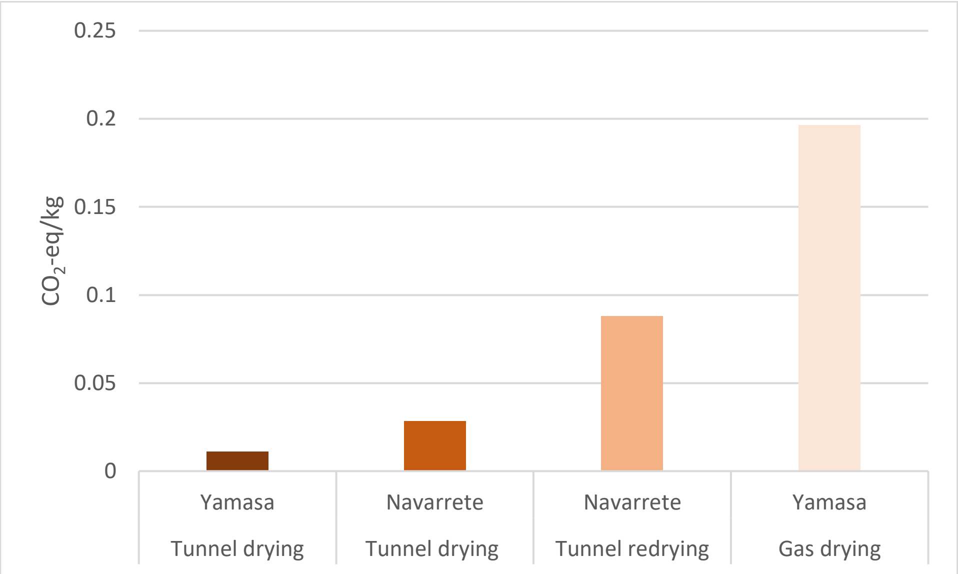


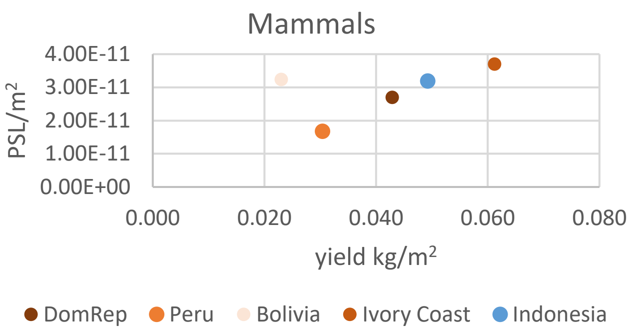
Figure 24 Global warming potential for 1 kg dried cocoa for 4 different drying options: 1: Standard tunnel drying in Yamasa and transportation to Medina, 2 Standard drying in Navarrete and transportation to Medina, 3: transportation from Yamasa to Navarrete, post-drying, and transportation to Medina, 4: Gas drying in Yamasa and transportation to Medina. According to IPCC (2021).

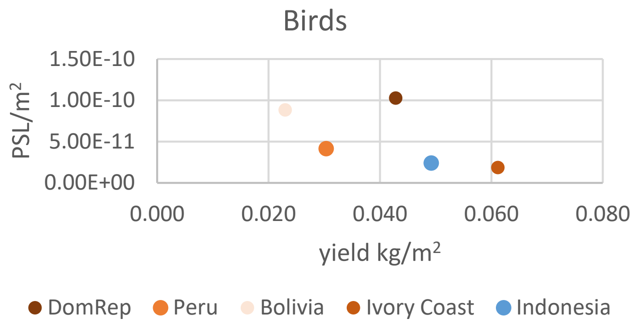
Appendix G: Global Characterisation factors for land occupation

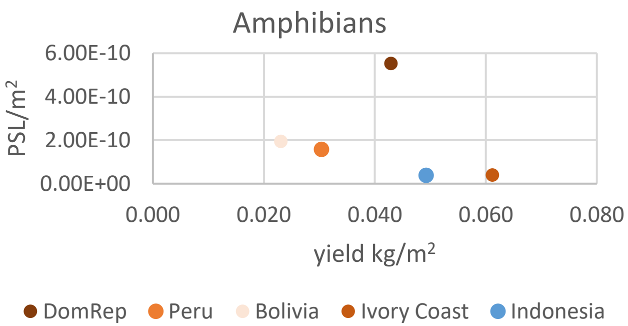
Table 8 Characterisation factors on both Ecoregion level and Country level according to (Chaudhary & Brooks, 2018). For each taxa, CF/m2 and weighted aggregated CF/kg cocoa are shown. The last column (difference) shows the difference between the aggregated PSL on country level and on ecoregion level.

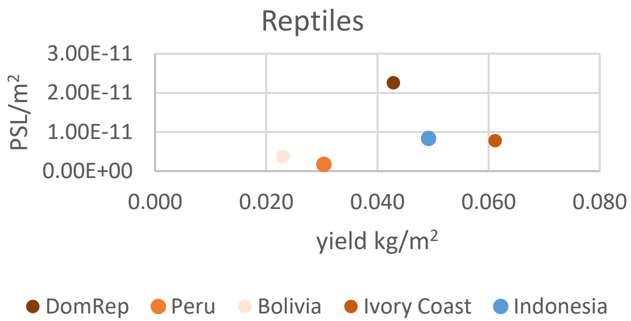
		Potential Species Loss (PSL) – Ecoregion						**Potential Species Loss (PSL) - Country**						
	Yield kg/ha*y	Mammals	Birds	Amphibians	Reptiles	Plants	Aggregated/m^2	Mammals	Birds	Amphibians	Reptiles	Plants	Aggregated/m^2	**Difference**
DR	23.34	2.7E-11	1.0E-10	5.5E-10	2.3E-11	3.3E-09	5.0E-08	2.8E-11	1.2E-10	4.9E-10	2.5E-11	4.4E-09	6.2E-08	+25%
BO	43.48	3.2E-11	8.8E-11	1.9E-10	3.7E-12	2.4E-10	2.4E-08	1.5E-11	2.1E-11	2.5E-11	1.3E-12	4.3E-11	4.6E-09	-81%
ID	20.33	3.2E-11	2.4E-11	3.8E-11	8.4E-12	1.8E-10	5.7E-09	5.2E-11	5.2E-11	4.5E-11	1.0E-11	3.8E-10	1.1E-08	+91%
PE	11.76	1.7E-11	4.1E-11	1.6E-10	1.8E-12	1.2E-10	4.0E-09	2.1E-11	4.7E-11	9.5E-11	2.7E-12	1.7E-10	3.9E-09	-3%
CI	16.35	3.7E-11	1.8E-11	4.0E-11	7.8E-12	6.2E-11	2.7E-09	2.0E-11	1.2E-11	2.2E-11	5.3E-12	3.0E-11	1.5E-09	-46%
GH	21.91	3.7E-11	1.8E-11	4.0E-11	7.8E-12	6.2E-11	3.6E-09	2.12E-11	4.7E-11	9.5E-11	2.7E-12	1.7E-10	7.4E-09	+103%

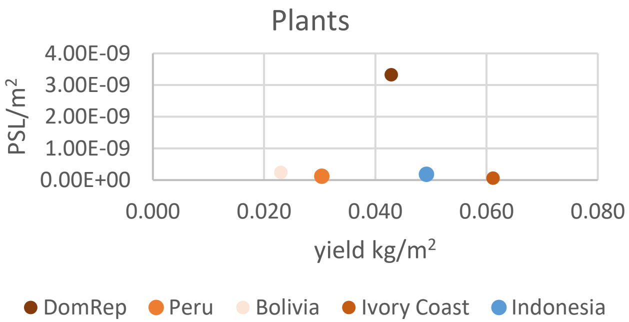
Appendix H - Taxa characterisation factors for global potential species loss (PSL)











Appendix I – Total global potential disappearing fraction of species

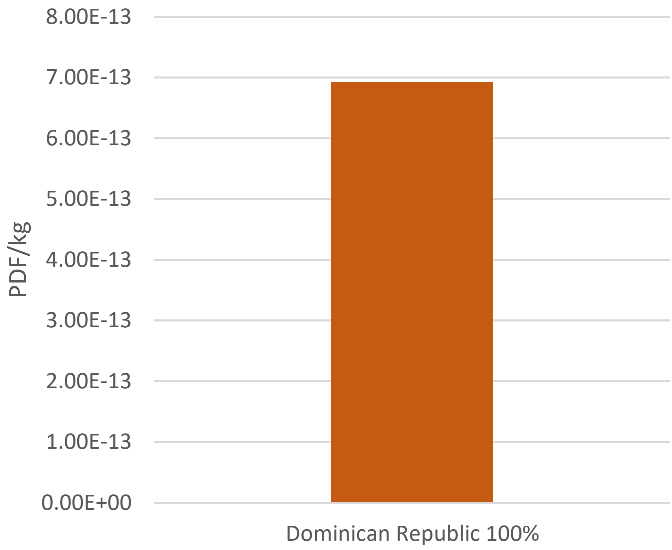


Figure 25 Land occupation related Potential Disappeared Fraction (PDF) of global species for 1 kg dried organic cocoa from the Dominican Republic, grown in the ecoregion Hispaniolan moist forest. According to the method from (Chaudhary & Brooks, 2018)

Appendix J - *Comparison of different methods and measurements of carbon sequestration for different countries and cultivation forms for cocoa.*

Table 9 Comparison of different methods and measurements of carbon sequestration for different countries and cultivation forms for cocoa.

Total t C / ha	Soil carbon stock (t C/ha)	Vegetation carbon stock (AGC), t C/ha	Dead biomass, t C/ha	Country	Comment	Source
80.8	66.4	14.4	-	DR	Cocoa beans	(Blonk Consultants, 2021)
202.9	65	133	4.9	DR	Native forest	
156.81				PE	adult cocoa systems	(Goñas et al., 2022)
133.59				PE	Young cocoa systems	
117+/-47	51	49	17		Cocoa = 18% of aboveground biomass, timber & fruit trees = 65% of aboveground biomass ➔ Big differences for agroforestry system, depending on shade tree density. ➔ Low density.	Somarriba et al (2013) Carbon stocks and cocoa yields in agroforestry systems of Central America
-	-	51-75			40% lower AGC (above ground carbon) for agroforestry compared to native forest.	Nijmeijer et al. (2019) Carbon dynamics in cocoa agroforestry systems in central cameroon
		118			Aboveground carbon	
100	29	57			Cacao-multi	Rajab et al (2016)
81.8 – 153.9	61.7 – 137.8	16.7 – 31.3			Biomass + Soil (60cm deep) Significantly higher Biomass C in shaded than unshaded systems.	Askia M. Mohammed et al (2016) Carbon storage in Ghanaian cocoa ecosystems
108.7					Organic management	Asigbaase et al. (2020) Biomass carbon stocks of organic and conv. Cocoa AF
76.3					Conventional management	

Appendix K - Comparison of the total environmental impact (ecological scarcity 2021) for cocoa from CI, DR, GH and ID

Table 10 Total environmental impact of 1 kg dried cocoa over its life cycle, for different midpoint categories for different countries, according to the total environmental impact (Frischknecht et al., 2021).

	CI		GH		ID		DR	
Land use biodiversity	40'303	51.7%	40'944	46.3%	160'924	62.2%	304'071	98.92%
Water pollutants	5'524	7.1%	7'011	7.9%	20'875	8.1%	27	0.01%
Global warming	11'218	14.4%	16'028	18.1%	40'943	15.8%	2'807	0.91%
Air pollutants	4'714	6.0%	6'653	7.5%	15'040	5.8%	142	0.05%
Pesticides (soil)	5'654	7.3%	8'293	9.4%	8'296	3.2%	17	0.01%
Heavy metals (soil)	6'040	7.7%	6'408	7.2%	6'761	2.6%	0	0.00%
Others	4'520	5.8%	3'163	3.6%	5'963	2.3%	316	0.10%
Total	**77'973**		**88'500**		**258'802**		**307'381**	

Table 11 Total environmental impact of 1 kg dried cocoa over its life cycle, for different processes for different countries, according to the total environmental impact (Frischknecht et al., 2021).

	CI		GH		ID		DR	
Land occupation & transformation	54'538	69.95%	63'084	71.28%	214'353	82.82%	306'562	99.73%
Pesticides & Fertilizer	18'925	24.27%	21'981	24.84%	40'914	15.81%	17	0.01%
Gas drying	0	0.00%	0	0.00%	0	0.00%	46	0.01%
Material & machines	2'450	3.14%	3'261	3.68%	3'167	1.22%	304	0.10%
Irrigation	1'893	2.43%	0	0.00%	0	0.00%	0	0.00%
Transport	166	0.21%	175	0.20%	368	0.14%	452	0.15%
Total	**77'973**		**88'500**		**258'802**		**307'381**	

Appendix L - Process share of total GWP

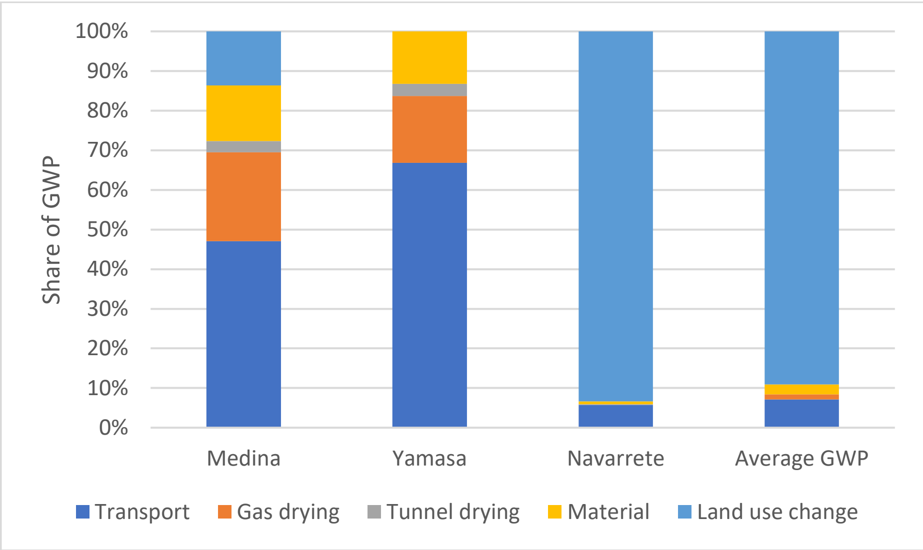


Figure 26 Process shares of the global warming potential of 1 kg dried organic cocoa for the different regions Medina, Yamasa and Navarrete and average

Appendix M – Literature comparison of yields from cocoa cultivation

*Table 12 Comparison of Yield kg/ha*y for 1 kg dried cocoa in different countries for different cultivation types and years.*

Yield kg / ha	Country	Cultivation type	Year	Source
136	CR	Agroforest	2011	(Deheuvels et al., 2012)
230	BO	Mixed monoculture (21%) and agroforestry (79%	2019	(Roth et al., 2020)
250	CI	Agroforest	2011	(Gockowski & Sonwa, 2011)
252	EC	Agroforest	2014	(Gockowski & Sonwa, 2011)
280	EC	Mixed monoculture and agroforestry	2020	(Froborg, 2022)
428	**DO**	**Agroforest**	**2022**	**This study**
479	GH	Agroforest	2011	(Gockowski & Sonwa, 2011)
503	EC	National average	2016-2021	(FAOSTAT, 2023)
527	DO	National average	2016-2021	(FAOSTAT, 2023)
530	UG	Mixed monoculture and agroforestry	2020	(Froborg, 2022)
850	PE	Agroforest	2022	(Pronatec, 2023c)

Appendix N – Inventory of the modelled datasets in SimaPro

The life cycle inventory is divided into the 3 phases *fresh cocoa*, *fermented cocoa* and *dried cocoa* including the scenarios (75% and 100% allocation). Further modelled data sets are listed below.

Table 13 Inventory of 1 kg fresh organic cocoa, including both scenarios with an allocation factor of 75% and 100%. Green: Resulting processes. Yellow: Inputs and outputs in technosphere and emissions. Blue: Indication of quantity for 1 kg of cocoa.

	Name	Unit	Fresh cocoa (DR) - 53%	Fresh cocoa (DR) - 75%	Fresh cocoa (DR) - 100%	Remarks
	Location		DR	DR	DR	
	Unit		kg	kg	kg	
Production	***Cocoa bean organic fresh {DR} at production site, (allocation 53%)***	kg	1			
	Cocoa bean organic fresh {DR} at production site, (allocation 75%)	kg		1		
	Cocoa bean organic fresh {DR} at production site, (allocation 100%)	kg			1	
From Nature	Occupation, permanent crop, DO	m^2a	4.41E+00	6.25E+00	8.33E+00	1200 kg yield/ha*y
	Carbon dioxide, in air	kg	9.76E-01	1.38E+00	1.84E+00	CO_2 uptake in biomass: from DS Cocoa bean {CI}| cocoa bean production, sun-dried | Cut-off, U
	Energy, gross calorific value, in biomass	MJ	1.25E+01	1.77E+01	2.36E+01	From DS Cocoa bean {CI}| cocoa bean production, sun-dried | Cut-off, U
	Transformation, from annual crop, DO	m^2	4.77E-03	6.75E-03	9.00E-03	1 ha/yield/50 years, 5.1% agriculture, 0.3% sugar cane
	Transformation, from forest, extensive, DO	m^2	2.24E-02	3.17E-02	4.22E-02	1 ha/yield/50 years, 25.32% forest
	Transformation, from permanent crop, DO	m^2	5.48E-02	7.75E-02	1.03E-01	1 ha/yield/50 years, 37.05% coffee, 3.3% other fruits
	Transformation, from grassland/pasture/meadow, DO	m^2	6.99E-03	9.89E-03	1.32E-02	1 ha/yield/50 years, 7.92% pasture field
	Transformation, to permanent crop, DO	m^2	8.83E-02	1.25E-01	1.67E-01	Transformation to cocoa plantation, 50 years
Materials	Glyphosate {GLO}| market for | Cut-off, U	kg	1.25E-04	1.25E-04	1.25E-04	Traceability 1.8%, 0.014 mg/kg in dry cocoa, application rate from: (Agrian, 2023)
	2,4-D, at plant/RER Economic	kg	4.81E-05	4.81E-05	4.81E-05	Traceability 2.7%, 0.005 mg/kg in dry cocoa
	Pesticide, unspecified {GLO}| market for | Cut-off, U	kg	5.49E-05	5.49E-05	5.49E-05	Chlorpyrifos: Traceability 0.7%, 0.005 mg/kg. application rate from (US EPA, 2014b) Since no specific dataset was available, pesticides unspecified was used.
	CO_2-eq from land use change	kg	8.84E-01	1.25E+00	1.67E+00	2001 kg/ha/1200*allocation, emissions calculated with BLONK-Tool

	Power sawing, without catalytic converter {RoW}| processing | Cut-off, U	hr	6.62E-05	6.62E-05	6.62E-05	Application hours were attained by producer statements. If the amount of petrol was stated instead of application hours, it was converted with the petrol use rate of Power sawing, without catalytic converter {RoW}| processing | Cut-off, U (Petrol consumption of 1.6kg/h, density of 0.75kg/l), leading to a total of 47.7 hours. These in turn were divided through the total yield of 716 t
	Horse {DR}, average size | Cut-off, U	p	4.06E-08	4.06E-08	4.06E-08	Life expectancy: 25 y 80 kg capacity, 15 km/day
	Mule {DR}, average size | Cut-off, U	p	1.75E-07	1.75E-07	1.75E-07	Life expectancy: 35 y, 85 kg capacity, 15 km/day
	Transport, passenger, motor scooter {GLO}| market for | Cut-off, U	personkm	9.96E-04	9.96E-04	9.96E-04	Assumed transported cocoa: 60 kg
	Transport, passenger car {RoW}| market for | Cut-off, U	km	3.13E-02	3.13E-02	3.13E-02	Assumed transported cocoa: 120 kg
	Cocoa seedling from orchard {DR}| Cut-off, U	p	1.88E-03	1.88E-03	1.88E-03	Transportation of the seedlings to the producers is not modelled
	Polypropylene container 150l	p	2.37E-06	2.37E-06	2.37E-06	Capacity of 150 l and a weight of 7 kg from (UDO BÄR & Partner AG, 2023)
Emisisons, air	2,4-D	kg	1.45E-06	1.45E-06	1.45E-06	3% into air. Emissions ratio taken from DS Maize, at farm/US-NC Economic, Application rate from (US EPA, 2014a)
	2,4-D, dimethylamine salt	kg	5.74E-08	5.74E-08	5.74E-08	Emissions ratio from DS Maize, at farm/US-NC Economic
	Chlorpyrifos	kg	1.41E-06	1.41E-06	1.41E-06	Emissions ratio from DS Maize, at farm/US-NC Economic
Emissions, water	2,4-D	kg	1.61E-08	1.61E-08	1.61E-08	0.33% into water. Emissions ratio taken from DS Maize, at farm/US-NC Economic
	2,4-D, dimethylamine salt	kg	6.38E-09	6.38E-09	6.38E-09	Emissions ratio from DS Maize, at farm/US-NC Economic
	Chlorpyrifos	kg	1.57E-07	1.57E-07	1.57E-07	Emissions ratio from DS Maize, at farm/US-NC Economic
Emissions, soil	Glyphosate	kg	1.25E-04	1.25E-04	1.25E-04	100% into soil. Emissions ratio taken from DS Coffee, green bean {HN}| coffee green bean production, arabica | Cut-off, U
	2,4-D	kg	1.44E-05	1.44E-05	1.44E-05	30.11% into soil. Emissions ratio taken from DS Maize, at farm/US-NC Economic
	2,4-D, dimethylamine salt	kg	5.74E-07	5.74E-07	5.74E-07	Emissions ratio from DS Maize, at farm/US-NC Economic
	Chlorpyrifos	kg	1.41E-05	1.41E-05	1.41E-05	Emissions ratio from DS Maize, at farm/US-NC Economic

Table 14 Inventory of 1 kg fermented organic cocoa, including both scenarios with an allocation factor of 75% and 100%. Green: Resulting processes. Yellow: Inputs and outputs in technosphere and emissions. Blue: Indication of quantity for 1 kg cocoa.

	Name	Unit	Fermented cocoa (DR) - 53%	Fermented cocoa (DR) - 75%	Fermented cocoa (DR) - 100%	Remarks
	Location		DR	DR	DR	
	Unit		kg	kg	kg	
Production	***Fermented cocoa, at processing centre, (allocation 53%)***	kg	1			
	Fermented cocoa, at processing centre, (allocation 75%)	kg		1		
	Fermented cocoa, at processing centre, (allocation 100%)	kg			1	
Materials	Cocoa bean organic fresh {DR} at production site, (allocation 53%)	kg	1.33E+00			
	Cocoa bean organic fresh {DR} at production site, (allocation 75%)	kg		1.33E+00		
	Cocoa bean organic fresh {DR} at production site, (allocation 100%)	kg			1.33E+00	
	Transport, freight, lorry 3.5-7.5 metric ton, euro3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	tkm	2.79E-02	2.79E-02	2.79E-02	Transport intermediary to processing centre: average of 21 km
	Fermentation bag Polyethylene - 500kg capacity	kg	7.35E-04	7.35E-04	7.35E-04	750 Fermentation bags à 2 kg in total per year
	Fermentation building, aluminium roof	m^2a	6.15E-04	6.15E-04	6.15E-04	
	Packaging bag Polyethylene - 60l	p	1.11E-02	1.11E-02	1.11E-02	Transportation bags white, 2x used, 60 kg volume
	Tap water {GLO}| market group for | Cut-off, U	kg	9.55E-03	9.55E-03	9.55E-03	Water consumption of 13 l/kg laundry according to ecoinvent dataset *Washing, drying and finishing laundry {GLO}| washing, drying and finishing laundry | Cut-off, U*
Waste treatment	Waste polyethylene/polypropylene product {GLO}| market for | Cut-off, U	kg	1.18E-02	1.18E-02	1.18E-02	Waste fermentation bags & packaging bags

Table 15 Inventory of 1 kg dried organic cocoa, including both scenarios with an allocation factor of 75% and 100%. Green: Resulting processes. Yellow: Inputs and outputs in technosphere and emissions. Blue: Indication of quantity for 1 kg cocoa

	Name Location Unit	Unit	Dried cocoa - 53% DR kg	Dried cocoa - 75% DR kg	Dried cocoa - 100% DR kg	Remarks
Production	***Dried cocoa bean organic {DR} cocoa bean at Harbour Antwerp (BE), mixed-dried | Cut-off, U, (allocation 53%)***	kg	0.99			Loss of 1% during packaging & sorting of the cocoa
	Dried cocoa bean organic {DR} cocoa bean at Harbour Antwerp (BE), mixed-dried | Cut-off, U, (allocation 75%)	kg		0.99		Loss of 1% during packaging & sorting of the cocoa
	Dried cocoa bean organic {DR} cocoa bean at Harbour Antwerp (BE), mixed-dried | Cut-off, U, (allocation 100%)	kg			0.99	Loss of 1% during packaging & sorting of the cocoa
Materials	Fermented cocoa, at processing centre, (allocation 53%)	kg	2.10E+00			
	Fermented cocoa, at processing centre, (allocation 75%)	kg		2.10E+00		
	Fermented cocoa, at processing centre, (allocation 100%)	kg			2.10E+00	
	Drying tunnel, plastic walls and roof, wooden construction {DR}|	m^2a	1.45E-03	1.45E-03	1.45E-03	Drying tunnel Yamasa modelled: Area from Goodle Maps: 4'510m^2, 1'555 t drying/y, assumption 50:50 wood & metal construction
	Drying tunnel, plastic walls and roof, metal construction {DR}|	m^2a	1.45E-03	1.45E-03	1.45E-03	Drying tunnel Yamasa modelled: Area from Goodle Maps: 4'510m^2, 1'555 t drying/year, assumption 50:50 wood & metal construction Modelling is the same as Drying tunnel, plastic walls and roof, wooden construction {DR}. Instead of wooden posts, metal posts (Steel, low-alloyed {GLO}| market for | Cut-off, U) are used.
	Gas oven, drying of cocoa	MJ	5.63E-01	5.63E-01	5.63E-01	Propane consumption 1.061 MJ/kg fresh cocoa (*J. Jocelyn, personal communication, 30 June 2022, Yacao SRL*), Factor 2.8 (140 kg fresh = 50 kg dried), Total of 19% dried with gas (27% Yamasa, 40% Medina) Heating value and density from: https://www.propan.ch/de/fluessiggas/eigenschaften
	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Cut-off, U	tkm	9.22E-02	9.22E-02	9.22E-02	Transportationto Medina for sorting & packaging 39%: 65 km yamasa - Medina, 40%: 167 km Navarrete - Medina
	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Cut-off, U	tkm	5.18E-02	5.18E-02	5.18E-02	Transportation Yamasa/Medina nach Navarrete dry finishing, Assumption 10% Yamasa to Navarrete (167 km)
	Sorting machine, dried cocoa	MJ	2.92E-02	2.92E-02	2.92E-02	31.15 l per 25 tons container cocoa, 0.506 kg/l propane
	Forklift {GLO}| market for | Cut-off, U	hr	3.61E-04	3.61E-04	3.61E-04	Assumption 1.5 h/d/location Based on an operating lifetime of 10'000 hours (Staplerexperte, 2023). (from Agricultural trailer {CH}| production | Cut-off, U) and a weight of 2.66 tons
	EUR-flat pallet {RER}| production | Cut-off, U	p	1.27E-04	1.27E-04	1.27E-04	Extrapolated from values Medina: 75 pallets per year for 590 tons of cocoa,
	Packaging bag Polyethylene - 60l	p	1.67E-02	1.67E-02	1.67E-02	Transportation bags 60 l volume, 1x used

	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U	tkm	7.61E+00	7.61E+00	7.61E+00	Transportation to Santo Domingo (DR: 18.42413,-69.63132) - Antwerp (BE: 51.26155,4.23730), calculated with: www.searates.com
	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Cut-off, U	tkm	8.40E-02	8.40E-02	8.40E-02	Transportation Medina - Santo Domingo
	Transport, tractor and trailer, agricultural {CH}| market for transport, tractor and trailer, agricultural | Cut-off, U	tkm	1.60E-04	1.60E-04	1.60E-04	Only applied in Navarrete (40% share of total cocoa). Assumed distance of 400m: Calculation: 0.4/1000*0.4
Waste treatment	Waste wood, untreated {GLO}| market for | Cut-off, U	kg	1.28E-03	1.28E-03	1.28E-03	Density of 300 kg/m^3 for soft sawnwood: https://www.swedishwood.com/wood-facts/about-wood/from-log-to-plank/properties-of-softwood/

Table 16 Inventory for 1p cocoa seedling from orchard. Green: Resulting processes. Yellow: Inputs and outputs in technosphere and emissions. Blue: Indication of quantity for 1p cocoa seedling

	Name	Unit	Cocoa seedling from orchard	Remarks
	Location		DR	
	Unit		kg	
Production	***Cocoa seedling from orchard {DR}| Cut-off, U***	p	1	
From Nature	Transformation, from grassland/pasture/meadow, DO	m^2	2.59E-03	
	Transformation, to urban, DO	m^2	2.59E-03	
	Occupation, urban, DO	m^2a	1.04E-01	
Materials	Gravel, crushed {BR}| market for gravel, crushed | Cut-off, U	kg	1.26E-01	Area 4x37.5x0.05=7.5 m^3, density of 2'000 kg/m^3 is taken according to the methodology guidelines of ecoinvent 2.2 (ecoinvent Centre, 2007).
	Polypropylene, granulate {RER}| production | Cut-off, U	kg	8.28E-04	Assumed life-time of 20 years
	Extrusion, plastic film {RER}| extrusion, plastic film | Cut-off, U	kg	8.28E-04	Assumed life-time of 20 years
	Steel, low-alloyed {GLO}| market for | Cut-off, U	kg	4.00E-03	Assumed life time of 20 years
	Packaging film, low density polyethylene {RoW}| production | Cut-off, U	kg	1.00E-02	Packaging bags 10 grams, Polyethylene
	Irrigation {DO}| irrigation, sprinkler | Cut-off, U	m^3	4.50E-02	2500 seedlings/year, *(N. Merky, personal communication, 10 February 2023, Pronatec AG)*
Waste treatment	Waste polypropylene {GLO}| treatment of waste polypropylene, open burning | Cut-off, U	kg	8.28E-04	Assumption: open burning
	Waste polyethylene {GLO}| treatment of waste polyethylene, open burning | Cut-off, U	kg	1.00E-02	Assumption: open burning
	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg	4.00E-03	

Table 17 Inventory for both 1 m² drying tunnel with wooden and metal construction. Green: Resulting processes. Yellow: Inputs and outputs in technosphere and emissions. Blue: Indication of quantity for 1m² of drying tunnel

	Name	Unit	Wooden construction	Metal construction	Remarks
	Location		DR	DR	
	Unit		kg	kg	
Production	***Drying tunnel, plastic walls and roof, wooden construction {DR}***	m^2a	1		
	Drying tunnel, plastic walls and roof, metal construction {DR}	m^2a		1	
From Nature	Occupation, urban, DO	m^2a	1.00E+00	1.00E+00	
Materials	Sawnwood, hardwood, air dried, planed {RoW}| market for | Cut-off, U	m^3	2.20E-03	2.00E-03	Wooden floor (30x8x0.03 m), including 0.715 m^3 for wooden poles for the wooden construction drying tunnel
	Ethylene vinyl acetate copolymer {RoW}| market for ethylene vinyl acetate copolymer | Cut-off, U	kg	3.15E-02	3.15E-02	A total of 91 kg sheet was used for the roof & side cover at an assumed 200 g/m²: https://www.hornbach.ch/shop/Foliengewaechshaus-200x300-cm-weiss/5647285/artikel.html
	Concrete, normal {RoW}| market for | Cut-off, U	m^3	8.00E-03	8.00E-03	Concrete foundation, measuring 30x8x0.2 m), with an assumed 20 cm thickness. lifetime of 25y,
	Steel, low-alloyed {GLO}| market for | Cut-off, U	kg	8.33E-02	8.33E-02	Steel platform. Assumed lifetime of 25 years, 500 kg
	Steel, low-alloyed {GLO}| market for | Cut-off, U	kg		7.50E-02	Metal poles. Assumed lifetime of 25 years, 450 kg
Waste treatment	Waste concrete {GLO}| market for | Cut-off, U	kg	1.95E+01	1.95E+01	Density of 2'440 kg/m³ according to dataset "Concrete, normal {CH} market for | Cut-off, U" (ecoinvent Centre, 2018).
	Waste plastic, mixture {GLO}| market for | Cut-off, U	kg	3.15E-02	3.15E-02	
	Waste wood, untreated {GLO}| market for | Cut-off, U	kg	1.54E+00	1.40E+00	Density of 700 kg/m³: https://www.anzugsmoment.de/werkstoffe/holz-gewicht/
	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg	8.33E-02	1.58E-01	

Drying oven: For the dataset ***Gas oven, drying of cocoa (DR)***, the ecoinvent dataset *Propane, burned in building machine {GLO}| propane, burned in building machine | Cut-off, U* was used as a basis. Dataset *Burning oven {DR}| production | Cut-off, U* was added (amount 1.18E-7).

Table 18 Inventory for the production of 1 burning oven (DR). Green: Resulting processes. Yellow: Inputs and outputs in technosphere and emissions. Blue: Indication of quantity.

	Name Location Unit	Unit	Drying oven DR p	Remarks
Production	***Drying oven {DR}| production | Cut-off, U***	p	1	Modelling of the burning oven in Medina. All values are estimations. The modelling is based on the ecoinvent data *Building machine {RER}| production | Cut-off, U*. For steel, electricity & heat, 10% of the values were taken.
Materials	Reinforcing steel {GLO}| market for | Cut-off, U	kg	7.00E+01	
	Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U	kg	3.00E+01	
	Concrete, normal {GLO}| market for | Cut-off, U	m^3	3.00E+00	
Electricity / Heat / Fuels	Electricity, medium voltage {RER}| market group for | Cut-off, U	kwh	9.17E+02	
	Heat, district or industrial, natural gas {RER}| market group for | Cut-off, U	MJ	9.00E+02	
Waste treatment	Waste concrete {GLO}| market for | Cut-off, U	kg	7.32E+03	Density 2'440 according to ecoinvent data *Concrete, normal {CH} market for | Cut-off, U*

Table 19 Inventory for each 1p horse and 1p mule over the entire lifetime. Green: Resulting processes. Yellow: Inputs and outputs in technosphere, and emissions. Blue: Indication of quantity.

	Name Location Unit	Unit	Horse DR p	Mule	Remarks
Production	***Horse {DR}, average size | Cut-off, U***	p	1		Assumed lifetime of 25 years, weight of 550 kg, carrying capacity of 80 kg, 15km transport distance/d

	Mule {DR}, average size | Cut-off, U	p		1	Assumed lifetime of 35 years, weight of 400 kg, carrying capacity of 85 kg, 15km transport distance/d. Entries for this dataset was according to the weight ratio compared to ds *Horse {DR}, average size | Cut-off, U (=73%)*
From Nature	Water, river, DO	l	3.19E+05	3.22E5	35 l/day for horse
Materials	Grass, organic {RoW}| grass production, permanent grassland, organic, extensive | Cut-off, U		3.65E+04	3.73E+04	4 kg/d for horse, assumed share of 80% grass, 20% concentrated feed
	Maize grain, feed {GLO}| market for | Cut-off, U		9.13E+03	9.33E+03	1 kg/d for horse
Emissions, air	Methane	kg	4.50E+02	4.60E+02	According to IPCC Guidelines (2006)

Table 20 Inventory for each cocoa from Ghana, Indonesia, and Ivory Coast over the entire lifetime. All inputs were taken from the original dataset (cells marked green) and added with sea freight transportation, taken from searates.com. Green: Resulting processes. Yellow: Inputs and outputs in technosphere, and emissions. Blue: Indication of quantity.

	Name Unit	Unit	Cocoa - Ghana kg	Cocoa Indonesia kg	Cocoa Cote Ivory Coast kg	Remarks
Production	***Cocoa bean {GH}| cocoa bean production, sun-dried | Cut-off, U***	p	1			All inputs an processes were taken from the original dataset. **Yield = 456.51 kg/ha**
	Cocoa bean {ID}| cocoa bean production, sun-dried | Cut-off, U			1		All inputs an processes were taken from the original dataset. Yield = **493.22 kg/ha**
	Cocoa bean {CI}| cocoa bean production, sun-dried | Cut-off, U - LUC angepasst	p			1	All inputs an processes were taken from the original dataset. Yield = **613.09 kg/ha**
Materials	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U	tkm	7.80E+00			Sea freight transport distances were added for a consistent comparison from https://www.searates.com/
	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U	tkm		1.65E+01		Sea freight transport distances were added for a consistent comparison from https://www.searates.com/
	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U	tkm			7.40E+00	Sea freight transport distances were added for a consistent comparison from https://www.searates.com/