Supplementary materials

S.1. Goal and scope and LCI

S.1.1 Transportation

Table S.1. shows the distances characterizing the itineraries of cocoa beans from the country of cultivation to the Italian manufacturing plant. The transportation means are “freight, lorry 16-32 metric ton, EURO3”, “freight, sea, transoceanic ship” and “freight, lorry 16-32 metric ton, EURO5” for transportation in the country of cultivation, sea transportation and transportation from the Italian harbor to the chocolate company, respectively.

Table S. 1. Distances of cocoa beans transportation. PE =’Peru’; GH=’Ghana’; CI=’Ivory Coast’; ID=’Indonesia’; DR=’Dominican Republic’ and UG=’Uganda’.

Itinerary		**Distance (km)**					
Start	End	PE	GH	CI	ID	DR	UG
cultivation site	departure port	340	307	441	260	60	1110
departure port	Italian port	11,280	6,480	6,480	11,577	8,240	8,262
Italian port	Manufacturing plant	195	195	195	195	195	195

The transportation of *other* cocoa beans is calculated considering a 50:50 ratio between Dominican Republic (DR) and Uganda (UG).

S.1.2 End of Life Treatment

The EoL treatments of the two packaging are modelled through average national scenarios of waste disposal and treatment (CiAl, 2014; Comieco, 2015). EoL scenarios are reported in Table S.2 together with the waste transportation distances assumed in this study.

Table S. 2. End-of-life scenario of packaging waste based on average national data and waste transportation distances.

End-of-life treatment	Aluminum foil	Cardboard	Distance
Recycling	74.3%	79.5%	50 km
Incineration	4.9%	8.6%	50 km + 50 km

Landfill	20%	11.9%	50 km + 50 km

S.1.3 Cocoa provisioning

The cocoa provisioning scenarios selected for the sensitivity analysis are included in the Ecoinvent 3.3 database: in Table S.3. the main information regarding the cultivations are reported. Cocoa from Indonesia (ID) is rain-fed (no irrigation), but it is characterized by the highest N- and K-fertilization rates. Ghanaian production (GH) has the highest water use, but zero N-fertilizers are applied. Finally, Ivorian cocoa beans are characterized by the highest productivity and highest pesticides application.

Table S. 3. Main information about cocoa beans from ecoinvent 3.3.

	Units	CI	GH	ID	RoW
yield	kg/ha	613	457	493	613
water	m^3/ha	985	1362	0	985
N	kg/ha	30	0	66	30
P	kg/ha	6	54	88	6
K	kg/ha	27	23	55	27
pesticides[a]	kg/ha	9.6	7.1	7.7	9.6

[a] active ingredient

S.2. Results and discussion

S.2.1 Overall process

Table S. 4 reports the total values of the considered environmental categories (CML-IA 2001 method) and the CED indicator referred to the FU, i.e. 1 kilogram of dark chocolate.

Table S. 4. Total absolute values (per FU) of the assessed impact categories obtained through the impact assessment method CML-IA 2001

Acidification	Eutrophication	Global warming	Photochemical oxidation	Ozone layer depletion	Abiotic depletion	CED
kg SO_2 eq	*kg PO_4^{3-} eq*	*kg CO_2 eq*	*kg C_2H_4 eq*	*kg CFC-11 eq*	*kg Sb eq*	*MJ*
2.26E-02	2.55E-02	2.62E+00	1.08E-03	5.70E-07	1.11E-05	33.75

To complete the analysis of the total environmental impacts caused by the FU, an uncertainty analysis is performed with the Montecarlo method through the SimaPRO software (Figure S. 1).

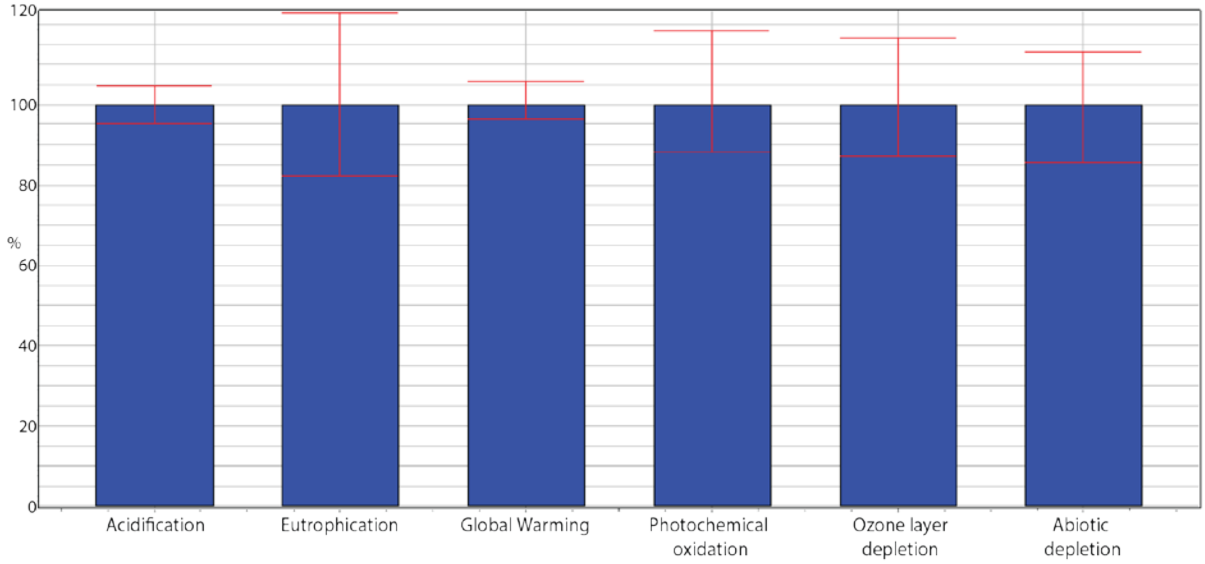

Figure S. 1. Results of the uncertainty analysis on the six impact categories considered in the study

Specifically, we establish the variability range of the calculated LCIA results due to uncertainty of data (i.e., the ones provided by databases). Eutrophication category presents the highest coefficient of variation (31%), while acidification and global warming (GWP 100) show the lowest (7.6% and 7.8%, respectively).

The Table S.5 shows the impacts of different unit processes to chocolate life cycle on seven categories.

Table S. 5. Breakdown of impacts of different phases to the dark chocolate life cycle.

oCB: *other* cocoa beans. Column 'Others' includes the production and transportation of jute and packaging, sugar transportation, and processes integrated in the downstream phase (i.e., distribution and EoL treatments).

Impact Category	Units	Sugar Prod.	Packaging Prod.	oCB cultiv.	Peruvian cultiv.	Transport Peru	Transport oCB	Trigenerator System	Manufact.	Others
Acidification	kg SO_{2eq}	2.52E-04	2.15E-03	1.40E-02	1.36E-05	1.77E-03	1.39E-03	1.56E-03	2.59E-04	1.13E-03
Eutrophication	kg $PO_4^{3-}{}_{eq}$	1.69E-04	5.91E-04	2.35E-02	2.35E-06	1.72E-04	1.52E-04	2.55E-04	1.69E-04	5.03E-04
Global warming	kg CO_{2eq}	3.40E-02	3.41E-01	1.10E+00	2.17E-03	1.07E-01	1.12E-01	5.74E-01	1.58E-01	1.91E-01
Photochemical oxidation	kg C_2H_{4eq}	3.81E-04	1.36E-04	2.70E-04	3.53E-07	5.49E-05	4.22E-05	1.07E-04	6.16E-05	3.11E-05
Ozone layer depletion	kg CFC-11_{eq}	5.05E-09	2.37E-08	3.60E-07	4.18E-10	2.02E-08	2.12E-08	1.02E-07	2.69E-08	1.05E-08

Abiotic depletion	kg Sb_{eq}	1.45E-08	1.47E-07	1.08E-05	3.95E-11	9.81E-10	1.24E-09	8.29E-10	1.14E-09	7.03E-08
CED	MJ	7.24E-01	5.16E+00	9.98E+00	3.26E-01	1.68E+00	1.76E+00	1.03E+01	2.77E+00	1.02E+00

S.2.2 CED

Figure S.2 shows the contributions of different unit process to the CED indicator. Excluding the energy embedded in biomass (e.g., cocoa and sugar), the manufacturing phase and the cultivation of *other* cocoa beans are the most consumptive phases. The total percentage of renewable resources is 4%, whereas for packaging production this fraction reaches 16%.

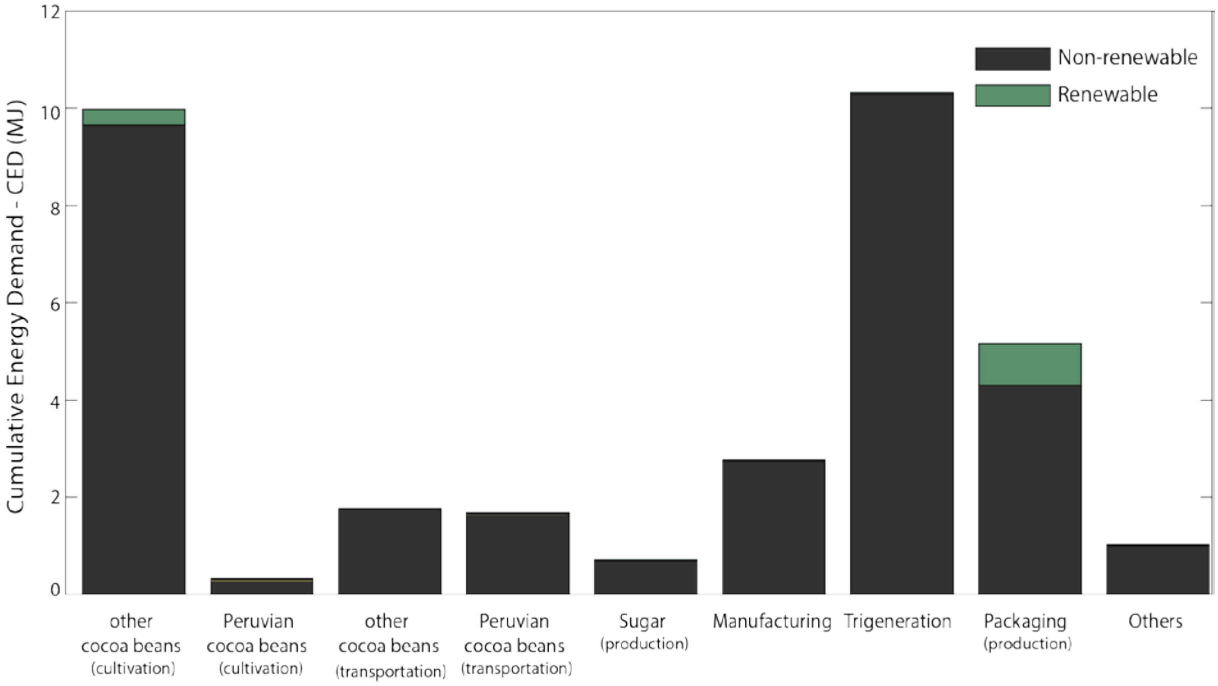

Figure S. 2 Cumulative Energy Demand (CED). The different contributions composing the CED indicator (MJ) are aggregated into non-renewable (fossil fuels e.g., oil, coal and gas) and renewable (solar, wind, water).

S.2.3 Sensitivity analysis

S.2.2.1 Cocoa Shells Allocation

The first sensitivity analysis regards the methodological assumption on cocoa shell allocation. Table S.6 contain the different allocation factors of shells, liquor, butter and powder used in the alternative scenarios (i.e. base scenario, the economic and the mass-based one). Figure S.3 shows the impacts of the three scenarios in the six considered CML-IA 2001 impact categories.

Table S. 6 Allocation factors of cocoa derivatives in three different scenarios.

RM	Base	Economic	Mass
Shells	0%	0.2%	13.1%
Liquor	100%	99.8%	86.9%
RMP	**Base**	**Economic**	**Mass**
Shells	0%	0.21%	13.5%
Liquor	38.4%	38.4%	33.3%
Powder	35.6%	23.9%	30.8%
Butter	26%	37.5%	22.5%

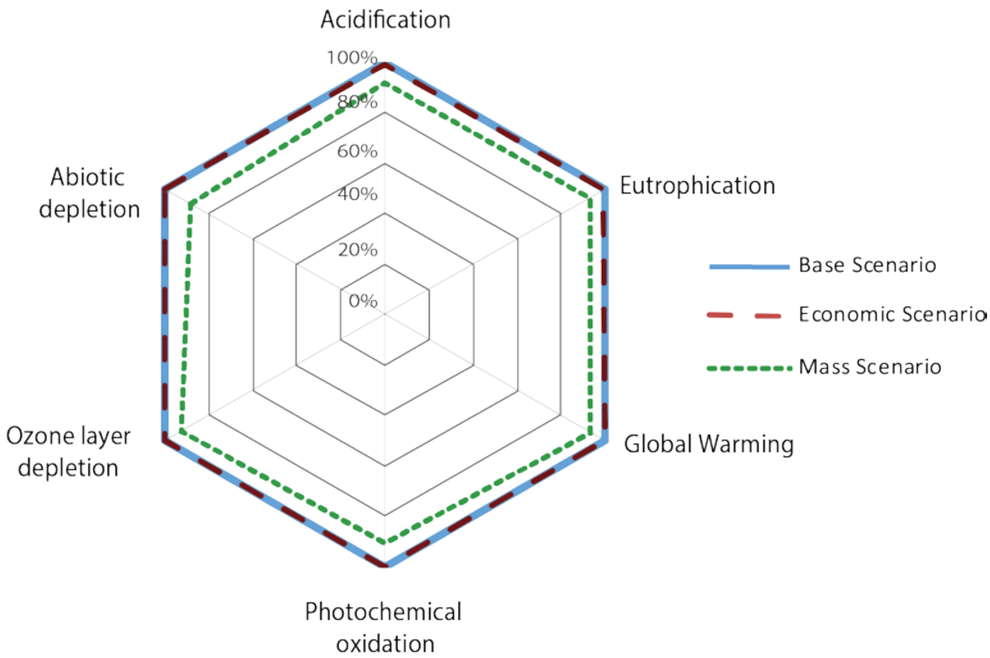

Figure S. 3. Impacts percentage, referred to the entire life cycle of dark chocolate, according to three different allocation scenarios

S.2.2.2 Cocoa Provisioning

Table S.7 reports the values of environmental impacts per FU obtained under the four cocoa provisioning scenarios.

Table S. 7. Comparison of the alternative cocoa provisioning scenarios. In the first four columns only the environmental impacts of cocoa provisioning are shown (cocoa cultivation and transportation to the chocolate manufacturing site), while in the last four the impacts of the overall chocolate life cycle are reported

Category	Unit	Cocoa provisioning	Chocolate Life Cycle

		BS	CI	GH	ID	BS	CI	GH	ID
Acidification	kg SO_{2eq}	1.72E-02	1.08E-02	8.51E-03	3.28E-02	2.26E-02	1.61E-02	1.39E-02	3.81E-02
Eutrophication	kg $PO_4^{3-}{}_{eq}$	2.38E-02	1.36E-02	1.64E-02	4.80E-02	2.55E-02	1.53E-02	1.80E-02	4.97E-02
Global warming	kg CO_{2eq}	1.32E+00	9.62E-01	8.73E-01	1.84E+00	2.62E+00	2.26E+00	2.17E+00	3.14E+00
Photochemical oxidation	kg $C_2H^4{}_{eq}$	3.67E-04	2.87E-04	3.53E-04	3.78E-04	1.08E-03	1.00E-03	1.07E-03	1.10E-03
Ozone layer depletion	kg CFC-11_{eq}	4.01E-07	3.92E-07	4.02E-07	4.21E-07	5.70E-07	5.61E-07	5.70E-07	5.89E-07
Abiotic depletion	kg Sb_{eq}	1.08E-05	9.45E-06	1.15E-05	1.27E-05	1.11E-05	9.68E-06	1.17E-05	1.29E-05
CED	MJ	1.37E+01	1.10E+01	1.50E+01	1.39E+01	3.37E+01	3.10E+01	3.50E+01	3.39E+01

A further step has been carried out to analyze four hypothetical *mono-origin* cocoa provisioning scenarios (100% for Peru, 100% from Ghana, 100% from Ivory Coast and 100% from Indonesia) and compare them with the base scenarios (BS). As Figure S.4 shows, the issue of impact variation due to agroecosystems variability is emphasized by the mono-origin scenarios. The highest variability occurs in the eutrophication category, whose values range between 1.53E-03 kg PO_4^{3-} eq (Peru) and 1.02E-01 kg PO_4^{3-} eq (Indonesia).

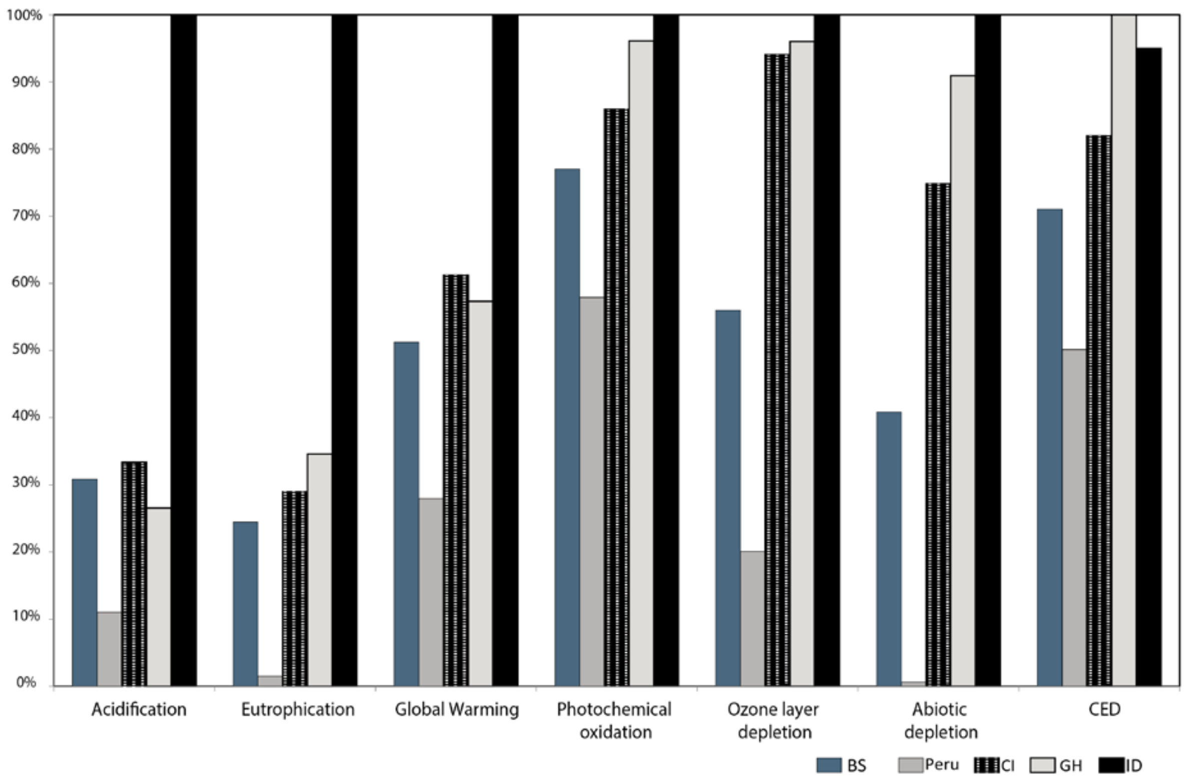

Figure S. 4 Comparison of mono-origin cocoa scenarios

S.2.2.3 Eco-toxicity of cocoa provisioning: comparison between scenarios

Since the effects of pesticide emissions are not included in the considered impact categories, we evaluate their impacts (referring to 1 kg of *other* cocoa beans) through the toxicity indicators included in the CML-IA 2001 baseline method: Human Toxicity (HT), Freshwater aquatic Eco-toxicity (FE), Marine aquatic Eco-toxicity (ME) and Terrestrial Eco-toxicity (TE). Despite the highest pesticides application rate per unit of area (Table S.3.), the cultivation of cocoa in Ivory Coast shows the lowest impacts on the four eco-toxicity categories, mainly due to the higher yield. Indonesia plantations have highest impacts on all categories, but for marine aquatic eco-toxicity for which Ghanaian production causes the highest impacts. This latter category shows the highest variability between scenarios: Ivory Coast cocoa has 30% less impacts than Ghanaian one.

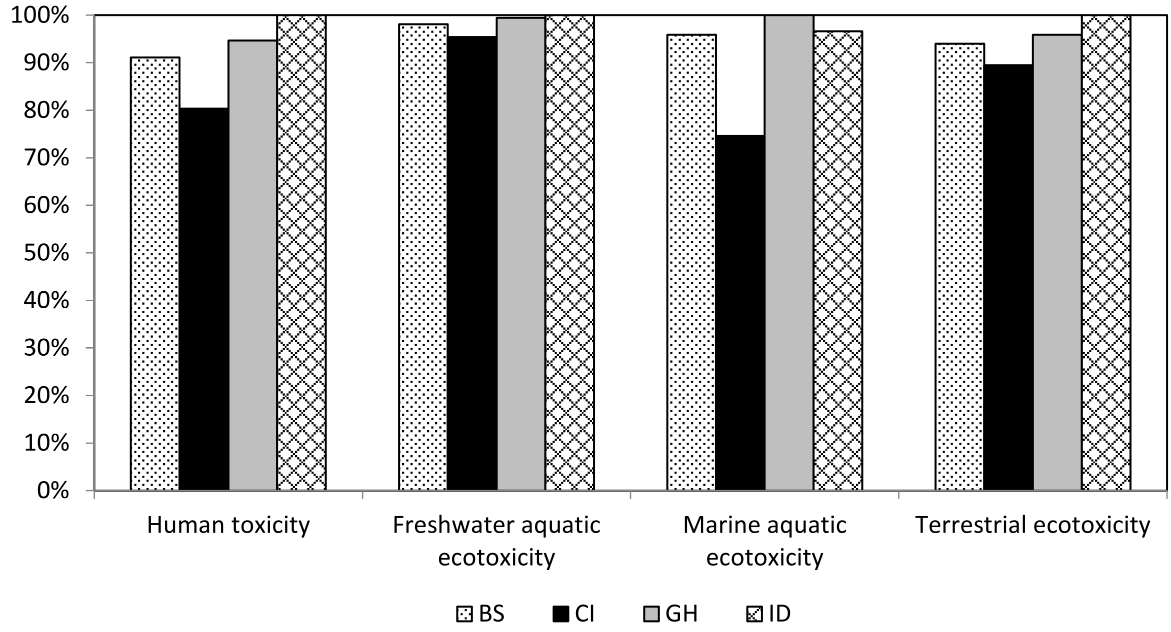

Figure S. 5. The results on eco-toxicity categories of LCIA concerning the cultivation of 1 kg of *other* cocoa beans. BS: Base Scenario, CI: Ivory Coast, GH: Ghana, ID: Indonesia

Table S. 8. Results for different provisioning scenarios on four eco-toxicity categories (1 kg of cocoa beans)

Category	units	Scenario			
		BS	CI	GH	ID
Human toxicity	kg 1,4 DB_{eq}	2.3	2.0	2.4	2.5
Freshwater aquatic eco-toxicity	kg 1,4 DB_{eq}	5.5	5.3	5.5	5.6
Marine aquatic eco-toxicity	kg 1,4 DB_{eq}	3590.1	2794.2	3744.7	3617.7
Terrestrial eco-toxicity	kg 1,4 DB_{eq}	0.114	0.123	0.128	0.120