The International Journal of Life Cycle Assessment (2023) 28:1495–1515
https://doi.org/10.1007/s11367-023-02142-4

LCA FOR AGRICULTURE PRACTICES AND BIOBASED INDUSTRIAL PRODUCTS

Environmental assessment of the Ecuadorian cocoa value chain with statistics-based LCA

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Received: 19 May 2022 / Accepted: 31 January 2023 / Published online: 17 February 2023

Abstract

Introduction Cocoa is one of the main crops grown in Ecuador. The agricultural area dedicated to cocoa represents the largest area dedicated to a permanent crop the country. Dry bean production has grown at an average annual rate of 15% since 2014, mainly due to yield improvements and replacement of other crops. Several varieties of cocoa are grown, but production is dominated by two main varieties: “Cacao Fino y de Aroma” and clonal varieties (dominated by CCN-51). Cocoa, mainly in monocrop systems, is mainly produced on the Ecuadorian Coast (but also in the Highlands and Amazonia). This study presents a statistics-based LCA of the Ecuadorian cocoa value chain.

Material and methods LCIs representing the various types of systems in each link of the value chain—i.e. the various types of farming systems, processing and distribution—were constructed in terms of representative production units. Sub-chains centred on different cocoa varieties and value-adding strategies were identified. Primary and secondary data were collected for the most representative system types, as defined in the actor typologies. Primary data were obtained via field visits and surveys, while secondary data were obtained mainly from statistical datasets of the National Institute of Statistics and Census. Impacts were computed following the European Commission's Product Environmental Footprint, while soil carbon turnover was modelled using RothC.

Results and discussion Identified types of producers are subsistence and entrepreneurial small, medium, and large. Two post-harvest strategies were modelled: a volume-oriented one and a quality-oriented one. The main sub-chains identified are the volume/commodity-oriented one (which is dominantly based on cocoa which either does not undergo post-harvest, or which undergoes volume-oriented post-harvest activities) and the quality-oriented one. Across producer types, irrigation and negative direct field emissions are the most important factors, followed in importance by total energy consumption. Post-harvest and processing activities are dominated by energy expenditures. Sub-chains feature significantly different intensity of impacts, with the volume-oriented sub-chain (i.e. those privileging quantity over quality) featuring lower impacts than the quality-oriented ones.

Conclusions The impacts of the value chain are comparatively lower, at least regarding climate change, than in other producing countries. Its agricultural phase generally exhibits low input pressure, contributes to climate change mitigation through high C sequestration in biomass that exceeds C losses due to land use change (e.g. deforestation), and does not seem to pose an immediate threat to biodiversity. Improvement initiatives do not necessarily imply intensification of production.

Keywords Biodiversity · Soil organic carbon · Value chain · Agroforestry · Monocrop

1 Introduction

1.1 Life cycle assessment of cocoa value chains

Life cycle assessment (LCA) has been widely applied in the context of interdisciplinary value chain analyses (Dabat et al. 2018a, b) and/or applied to study whole value chains (Hellweg and Milà i Canals 2014; Meinrenken et al. 2020). This is particularly true for agri-food value chains

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Communicated by Sergiy Smetana.

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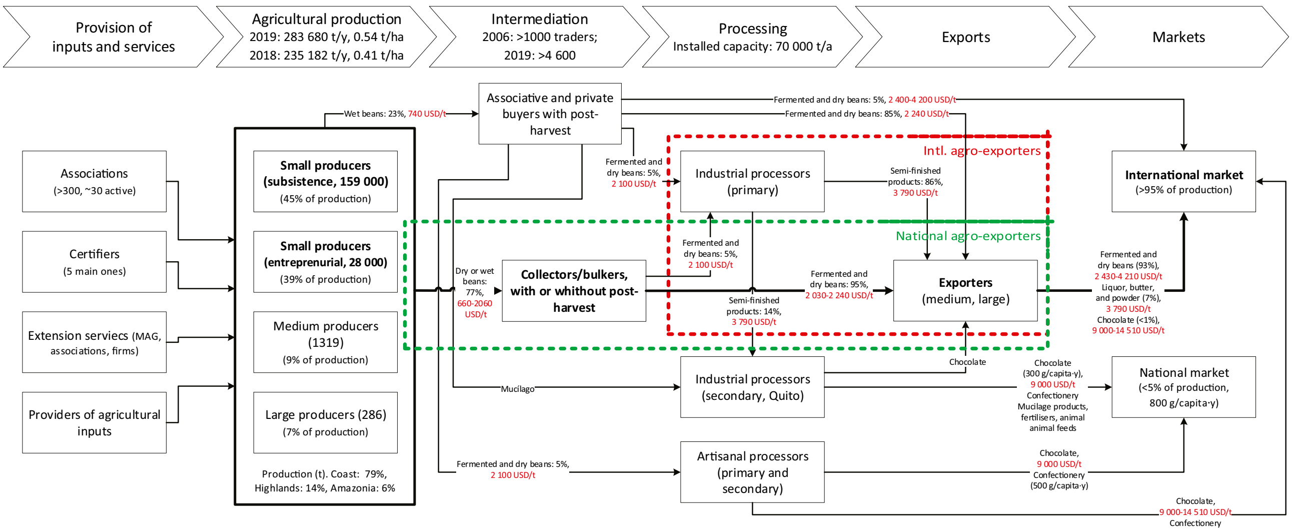

Fig. 1 Ecuadorian cocoa value chain flow diagram (2019). Source: (Avadí et al. 2021)

(Basset-Mens et al. 2021), including the cocoa and chocolate sector (Vesce et al. 2016; Recanati et al. 2018; Bianchi et al. 2020; Boakye-Yiadom et al. 2021).

Despite the publication of various Ecuadorian cocoa value chain studies (CEPAL 2014; Vassallo 2015; Acebo 2016; Ríos et al. 2017; Guilcapi 2018; Henry et al. 2018; Barrera et al. 2019; INIAP 2019; FAO and BASIC 2020), applying different methodologies and exploring in varying degrees of depth different elements of the value chain functioning, no comprehensive environmental assessment has been published to date. Existing partial analyses include, for instance, a recent energy assessment focused on climate change (Pérez Neira 2016) and various studies on cadmium (Chavez et al. 2015; Barraza et al. 2017; Argüello et al. 2019), as well as studies on biodiversity and carbon sequestration associated with cocoa plantations (e.g. Jadán et al. 2015; Samaniego et al. 2017).

This study presents a detailed statistics-based life cycle assessment (LCA) of the Ecuadorian cocoa value chain, produced in the context of the latest available value chain study (Avadí et al. 2021). The value chain study performed a functional analysis as a starting point for socio-economic and environmental analyses, including a detailed mapping of the chain, which facilitates detailed environmental assessments, as discussed in Acosta-Alba et al. (2022). The use of statistical data to inform life cycle inventories is not uncommon (Moreau et al. 2012; Weymar and Finkbeiner 2016; Avadí et al. 2017; Pradeleix et al. 2022), even for the construction of life cycle inventories databases such as AGRIBALYSE (Koch and Salou 2016; Asselin-Balençon et al. 2020) and Agri-footprint (Blonk Consultants 2019).

1.2 The Ecuadorian cocoa value chain

Cocoa is one of the main crops grown in Ecuador. The agricultural area dedicated to cocoa (601 954 ha in 2019, or 4% of total land use) represents the largest area dedicated to a permanent crop the country: 38% in the period 2014–2019, followed by oil palm and banana with 18% and 12%, respectively. Dry bean production, which reached 283 680 t in 2019, has grown at an average annual rate of 15% since 2014. Such growth has been achieved mainly by improving yields and by replacing failed oil palm areas with cocoa, as demonstrated in Avadí et al. (2021) (see key historical surface and yield statistics in the Supplementary Material). Several varieties of cocoa are grown in Ecuador, but production is dominated by two main varieties: "national" or Cacao Fino y de Aroma (CFA, 43% of area and 28% of production in 2017) and clonal varieties, chiefly CCN-51 (57% of area and 72% of production in 2017). Cocoa is mainly produced on the Ecuadorian Coast (but also in the Highlands and Amazonia), and its value chain is highly complex (Fig. 1). Cocoa systems are dominantly monocrop plantations, but 13% of the cocoa surface consists of associated systems, mostly cocoa trees associated with food crops, but to a lesser extent (2–3%), agroforestry systems, mostly in the Amazonia (Avadí et al. 2021).

The functional analysis presented in Avadí et al. (2021) identified several key value chain structural features, namely, a typology of actors (Supplementary Material) and the existence of five sub-chains.

Among intermediaries, several strategies were identified, which are closely related with the sector's main sub-chains. These strategies consist of commercial brokering of unfermented beans dried on farm or along roadsides, and two types of post-harvest performed at collection centres (quality-oriented and volume-oriented). The former usually ferments wet beans in wooden crates and dries them under a plastic tunnel, often on wooden drawers or on concrete surfaces. The latter allows the wet beans to ferment for a short time on woven plastic bags and dries those using thermal means (gas, diesel).

A small percentage of beans that undergo fermentation and drying (i.e. < 10%) are further processed by artisanal or industrial means. Industrial and artisanal processing differs, rather than in terms of technology or scale, in terms of the interconnectivity between the different processes. Cocoa processing is broadly divided into two stages: primary and secondary processing. Often, both stages are integrated.

Primary processing consists of roasting the beans, grinding (with shell separation), crushing to obtain liquor, and as an optional step the separation of the liquor into its components butter and powder. These products are collectively referred to as "semi-processed". Secondary processing consists of combining the products of primary processing with other ingredients (milk, sugar, and possibly aromatic ingredients in small quantities) to produce chocolate. There are different types of chocolate, but broadly speaking, we speak of industrial chocolate (e.g. couverture) or consumer chocolate (dark, milk, white). In addition to the raw material, cocoa processing consumes energy (usually electricity) and very little water. The processing technologies and processes applied in Ecuador are rather standard, and have been described in numerous publications (Pérez Neira 2016; Recanati et al. 2018; Abad Merchán et al. 2020; Bianchi et al. 2020; Ramos-Ramos et al. 2020), including artisanal processing (Aguilar Jaramillo 2005).

The five identified key sub-chains consist of various interlinkages of different types of actors and actors' strategies across the value chain (Supplementary Material):

- An agro-industrial "volume" sub-chain that seeks economies of scale on volumes: It is structured around collection centres of collectors/brokers (practicing thermal drying) supplied by small producers, focuses on large volumes of commodity cocoa (i.e. cocoa beans of industrial quality, often under-fermented, dominated by CCN-51 but including as well "commodified" CFA), makes blends, and supplies national agro-exporters and transnationals. Transnationals seek to integrate the supply of raw materials with their international links (value addition outside Ecuador) and in principle seek traceability.
- A "quality" sub-chain based on CFA: It is structured around private or corporate collection centres, mostly provided by large producers who carry out fermentation in crates; it focuses on moderate volumes of CFA to be exported as beans by national agro-exporters. Produces smaller quantities of semi-processed products.
- A "semi-processed" production sub-chain: It is structured around a small group of primary, industrial processors, which use cocoa blends to produce semi-processed products (i.e. liquor, butter, powder) mainly for the international market. They are mainly sourced from small producers.
- A "premium" sub-chain: It is structured around medium-sized producers who produce very high-quality CFA, in very small volumes, traded (after careful post-harvesting) at very high prices on the international market. Batches of grain sold at up to > 12 000 USD·t^{-1} have been documented.
- Transversally to these four sub-chains, an "organic" sub-chain can be identified: Linked in many cases to Fairtrade certification (and therefore similar to the "premium" sub-chain), it is structured around a handful of associative collection centres or with cooperative statutes. This sub-chain represents a very low weight in terms of volume and value, not due to a lack of demand, but of supply capacity (as the organic price differential does not compensate for the certification costs).

2 Material and methods

2.1 Goal and scope

The LCA-based environmental assessment of the cocoa value chain and sub-chains in Ecuador aims to determine the potential impacts of its current functioning on the three classical areas of protection. To estimate these impacts, life cycle inventories representing the various types of systems in each link of the value chain (i.e. the various types of farming systems, artisanal and industrial processing and distribution), were constructed in terms of representative production units. To do so, mostly secondary data were collected for the most representative system types, as defined in the actor typologies (Supplementary Material). Scarce primary data were also obtained via field visits and surveys and used mainly for confirmation of trends. Secondary data, from which agricultural inventories were built, were obtained from various sources:

- The main secondary source, especially of quantitative information, from which the data on the cocoa value chain (in its primary link) was obtained, is the statistical datasets of the National Institute of Statistics and Census (INEC). Every year, INEC carries out a field investigation of the agricultural and livestock sector, through which it collects information on the different agricultural and livestock activities carried out in the country, in order to publish the Continuous Agricultural Surface and Production Statistics during the first quarter of each year. For this purpose, it carries out field operations in the last quarter of each year, where it applies the so-called Survey of Continuous Agricultural Surface and Production (ESPAC, https://www.ecuadorencifras.gob.ec/estadisticas-agropecuarias-2/), which provides information on the production of an annual period and was designed with different reference periods. The resulting databases focus on the agricultural phase only, excluding agro-industry. The ESPAC datasets for 2018 and 2019 were retrieved at a higher level of detail than the officially published data (V. Bucheli, INEC, 04/2020, pers. comm.). The ESPAC 2019 dataset includes ~ 5 500 data points (i.e. individual farms).

- Another important source of data was the repository of the Agricultural Public Information System (SIPA, http://sipa.agricultura.gob.ec/) of the Ministry of Agriculture and Livestock (MAG). This repository includes a land use map that includes details on the types of crop associations (absent in the ESPAC data).
- The Technical Assistance Project for Post-Earthquake Productive Reactivation (Gobierno del Ecuador 2017) funded by the European Union (1.77 USD million) contracted in 2018 an International Technical Assistance with the objective of designing a Competitive Improvement Plan for the Cocoa—Chocolate chain, which contributes to “boosting agro-industrial, inclusive, differentiated and competitive development”. The results of this technical assistance include a participatory diagnosis of the value chain (Henry et al. 2018) and a competitive improvement plan for the year 2025 (Salgado et al. 2019). The primary data obtained during this technical assistance were used here as secondary data.

The scope (boundaries) of the study includes, as limited by data availability and quality, (i) all types of producers, further segregated by region and cocoa variety; (ii) two types of post-harvest operations; iii) primary and secondary transformation; and (iv) separate analyses for the identified sub-chains (from agricultural production to export).

Two main functional units were retained for the agricultural phase: 1 t of cocoa (in dry bean equivalents) and 1 ha of cocoa production, at farm gate. For semi-processed and processed products, 1 kg of product was retained, at factory gate.

The allocation of impacts among co-products was not necessary, since, from an environmental point of view, it is not necessary to separate the co-products of primary processing (liqueur, butter, and powder; see Supplementary Material), when they are considered together as the output of the process (data paucity prevented disaggregating these co-products). When modelling cocoa systems under cultural associations, the data used were sufficiently segregated to identify the specific agricultural inputs to cocoa in these associations.

2.2 Inventories

Life cycle inventories were constructed using as the main data source (for the agricultural phase) the ESPAC 2019 database, complemented by other sources used to inform specific details, approximations, and assumptions. The ESPAC 2019 data were treated as follows:

- The database was manipulated to select the 5 495 records representing cocoa farms (plots producing different varieties are represented separately in the database) and to obtain averages and standard deviations for each type of producer, by region and by variety of cocoa produced.
- The database presents data reported in terms of production of “wet” beans (with pulp) and dry beans, as well as wet:dry beans conversion factors per farm. Using these coefficients, farm data were standardised in terms of dry beans. Using the resulting aggregated and normalised data, preliminary LCIs were constructed, but some inputs required additional manipulations.
- Pesticide use data are reported in ESPAC in terms of label colour, which in Ecuador corresponds to toxicity levels defined by the Agency for Plant and Animal Health Regulation and Control (AGROCALIDAD, https://www.agrocalidad.gob.ec/). Based on the literature, the most commonly applied products were identified and average products were constructed, assuming identical proportions between products in each pesticide category (Supplementary Material).
- The percentage of farms (by type, region and variety) that practiced pruning (i.e. thinning) was obtained from the ESPAC 2018, as this datum was not included in the ESPAC 2019.
- An assumption on mechanisation levels (e.g. use of motor mower/trimmer) was applied to estimate the number of mechanised labour hours associated with each type of producer: small producers at 0%, medium producers at 50%, and large producers at 100% mechanisation.
- The water needs of cocoa plants, used to estimate irrigation levels in combination with the percentages of irrigated area by type, region, and variety, were determined between 1500 and 2 500 mm·ha^{-1}·year^{-1} (Gaibor Pozo 2017).
- Nitrogen requirements of cocoa plants, used to estimate direct emissions, were determined at 400 kg N·ha^{-1} for plants aged between 5 and 12 years, based on data from Applied Agricultural Resources (http://www.aarsb.com.my/cocoa-fertilizer-requirements). Other data needed to inform the direct emissions estimation models used—

Table 1 Basic formulations of chocolate products

Ingredients	Inclusion rates in chocolate products		
	Industrial/couverture	Consumption—dark	Consumption—milk
Cocoa liqueur	69%	42%	25%
Sugar (local, imported)	20%	14%	40%
Milk powder (imported)	11%	0%	20%
Cocoa butter		28%	15%
Cocoa powder/cake		16%	0%

Source: Interviews with chocolate producers and Bianchi et al. (2020)

Indigo-N v3 (Bockstaller et al. 2022), IPCC 2019 (Ogle et al. 2019) and ecoinvent (Nemecek and Schnetzer 2012)—were obtained from different sources (Nemecek and Schnetzer 2012; Koch and Salou 2016; Barraza et al. 2017; Ogle et al. 2019; Galland et al. 2020). The choice of direct field emission models for N was based on the discussion in Avadí et al. (2022).

- The amounts of C sequestered in above and below ground biomass of cocoa plants were estimated, by type, region, and variety, based on plantation age, growth curves, planting densities, and C content per unit of dry matter, from various sources (GIZ 2011; Fischer 2018; Galarza Ferrín 2019).
- Key parameter values required to determine the total C inputs to the soil and the C sequestered in the cocoa plants during the life cycle of the plantations were extracted from the literature. They include the biomass and C in the cocoa plant (see above), the biomass and C in pruning residues (average of pruning types: maintenance, light, drastic) (Engracia Manobanda 2018), and the biomass and C in harvest residues (Martínez-Ángel et al. 2015; Estrada León 2018). C content of cocoa biomass was estimated at 0.475 of dry matter (Galarza Ferrín 2019). Estimations of C in agroforestry systems' biomass was obtained from various sources. Biomass C sequestration in Amazonian agroforestry cocoa systems was estimated at 2.89 t $C \cdot ha^{-1} \cdot year^{-1}$ for cocoa trees and 4.20 t $C \cdot ha^{-1} \cdot year^{-1}$ for all other species, based on data in Torres et al. (2014). For Andean agroforestry systems, 5.34 t $C \cdot ha^{-1} \cdot year^{-1}$ were estimated for cocoa trees plus all other species, based on data in Schneidewind et al. (2019). Both estimates were integrated into the inventories per ha of agroforestry systems. For Amazonian systems, the accumulated necromass reaches 0.59 $t \cdot ha^{-1} \cdot year^{-1}$ for agroforestry systems and 0.56 for monoculture systems (Torres et al. 2014). Necromass represents an additional contribution of organic matter to soil organic carbon (SOC) sequestration.
- Yields were amortised to account for non-productive years, based on MAG data suggesting that CCN-51 systems start to be productive from the 3rd year and CFA systems from the 3rd or 4th year, and following suggestions from the literature on the importance of such amortisation (Bessou et al. 2013, 2016). The resulting amortisation factors were 69% (of annual yield) for CCN-51 and 62% for CFA. The World Food LCA Database (WFLDB) inventories of perennial systems (Nemecek et al. 2020) also take non-productive years into account, but not the ecoinvent (Wernet et al. 2016) or AGRIBALYSE inventories (Koch and Salou 2016; Asselin-Balençon et al. 2020).
- It was assumed that 100% of applied pesticides end up in the soil compartment (Nemecek and Schnetzer 2012), although more complex modelling has been shown to be necessary (Gentil-Sergent et al. 2021). Such modelling is onerous, and less necessary for cocoa in Ecuador, which is generally a low pesticide use system.
- Median values were retained for impact computations, instead of means, due to large standard deviations and to the non-normal nature of the data (results based on mean values for the agricultural phase are presented in the Supplementary Material). Triangular distributions based on minimum, median, and maximum values for each parameter were used for uncertainty propagation (with Monte Carlo).
- Finally, the inventories by type, region, and variety were further disaggregated to differentiate between monoculture and cultural association systems (agroforestry and other association systems).

The inventories of post-harvest processes were modelled on the basis of primary data (10 datasets). The inventories of the transformation processes, including average formulations of processed cocoa products, were modelled on the basis of primary data (3 datasets) and secondary data (4 datasets: Ntiamoah and Afrane 2008; Pérez Neira 2016; Recanati et al. 2018; Boakye-Yiadom et al. 2021), basically in terms of energy consumption. Processing does not consume chemicals, and water consumption is marginal. Ingredients other than cocoa derivatives (sugar, milk powder), as well as complementary/auxiliary processes (production of electricity, packaging materials, fertilisers, pesticides and fuels, combustion, infrastructure), were obtained from LCI databases (Koch and Salou 2016; Wernet et al. 2016; Nemecek et al. 2020). The formulations of three types of chocolate were established from primary and secondary data (Table 1).

Intermediation and transport—to collection centres all over the country, to processing in Quito where cocoa semi-processing and processing plants are concentrated, and to the port of Guayaquil from where most export originates—were modelled on the basis of average distances transported (Amazonia to Guayaquil: 450–650 km, Amazonia to Quito: 200–300 km, Highlands to Guayaquil: 360 km, Highlands to Quito: 110 km, Coast to Guayaquil: 180–370 km, Coast to Quito: 230–510 km), inspired by the literature (Pérez Neira 2016).

A series of aggregate processes (e.g. weighted averages between regions, between regions and cocoa varieties, national average) were calculated for the analysis:

- Beans (dry equivalent), large producer [CCN-51, CFA, total].
- Beans (dry equivalent), medium producer [CCN-51, CFA, total].
- Beans (dry equivalent), small producer micro-entrepreneur [CCN-51, CFA, total].
- Beans (dry equivalent), small subsistence producer [CCN-51, CFA, total].
- Beans (dry equivalent), national average [CCN-51, CFA, total].
- Ecuadorian chocolate, national average [production-weighted mean of cocoa origins and varieties, and chocolate types as defined in Table 1]; from secondary processing.

2.3 Impact assessment

The life cycle impact assessment methods recommended by the European Community's Product Environmental Footprint (PEF) initiative (EC 2013) were applied. The updated list of methods presented in the recent Product Environmental Footprint Category Rules Guide (Version 6.2—June 2017, (Zampori and Pant 2019)) was used, as available in SimaPro v9.2 (method: EF v3.0). The EF 3.0 method does not take into account carbon sequestration in biomass (Carbon dioxide, in air), whereas other methods, e.g. ILCD 2011 Midpoint + V1.11 (EC-JRC 2012), do take into account such sequestration (incorrectly for annual crops, but correctly for perennials). Therefore, the EF 3.0 method was modified to replace the characterisation factor of "Carbon dioxide, in air" from 0 to – 1. This logic complies with the consensual definition of "carbon sequestration", which implies a net removal of C from the atmosphere to be stored in a long-term reservoir, be it soil and biomass. (Agostini et al. 2015; Chenu et al. 2019).

This list of midpoint indicators was complemented with ReCiPe endpoint indicators (2.2 Endpoint World H/A (Hierarchy/Average)). ReCiPe was chosen because it presents endpoint indicators in all three areas of protection, based on many relevant impact categories (Huijbregts et al. 2016). The hierarchical perspective (H) was chosen because it is based on the most common normative principles with respect to timeframe and other issues and is therefore often found in scientific models (Goedkoop et al. 2013).

Moreover, key considerations, such as the contribution of C sequestration in biomass (C sequestration in plant biomass is considered in the climate change impact category as negative emissions) and soils to climate change, and land use change impacts on biodiversity, were explicitly modelled.

Biomass and thus C accumulation in biomass by different types of cocoa systems were determined from the literature, as described in Section 2.2. SOC sequestration associated with the different systems was estimated using the RothC model (Coleman and Jenkinson 2014), based on initial soil C content, annual inputs of organic matter (residual above- and belowground biomass, such as pruning and harvest residues, and necromass, plus organic fertilisers), and local pedoclimatic conditions (precipitation, evapotranspiration, temperature, soil density, soil clay content, etc.), according to the method and data sources described in Albers et al. (2022). The R script and CSV files with input data are included in the Supplementary Material. Two types of global agroecological zones (GEZ) (Fischer et al. 2012) were considered for the coastal region. Simulations had durations of 10 years for CCN-51 systems and 20 years for CFA systems (national average plantation ages reported in ESPAC 2019 are 8 and 24, respectively). Soil erosion by rainfall was considered, using the RUSLE2 model (Foster 2005), as soil erosion implies SOC losses (Lugato et al. 2016). The most dominant soil types in the different regions were chosen, according to two contrasting sources (FAO/IIASA 2009; Quesada et al. 2011).

A recent report (Deteix 2021) compared different theoretical frameworks for estimating biodiversity impacts associated with agricultural activities. Based on this report, UNEP recommendations (UNEP 2016, 2019), and CIRAD recommendations on LCA practice in developing and transition economies (Basset-Mens et al. 2021), the method described in Chaudhary and Brooks (2018) was retained. This method provides characterisation factors for land use (and land use change) impacts by country and ecoregion (Olson et al. 2001), expressed in terms of potential disappeared fraction of species per unit area (PDF·m^{-2}), which includes five taxa (plants, mammals, birds, amphibians, and reptiles).

Water resource depletion was not explored, because water for agricultural use is relatively abundant in Ecuador (21% access to irrigation, yet only 20 out of > 4 000 sampled farms declared losses due to water deprivation), and several infrastructure projects facilitate access, although not without problems (Salmoral et al. 2018; Mohammadpour et al. 2019).

3 Results and discussion

3.1 Life cycle inventories

The resulting agricultural inventories are in the form described in Table 2 and presented in the Supplementary Material. The post-harvest and processing inventories are presented in Tables 3 and 4. The large difference in input intensity between mean and median-based inventories is noticeable and is further explored in Section 3.3.

Values presented consists of means followed by medians (in parenthesis).

3.2 Absolute and relative impacts

The assessment of cocoa production impacts, disaggregated stepwise by producer type, region, cocoa variety, and system type, suggests several overlapping dynamics.

For instance, impacts per ha of cocoa increase along the gradient of *producer types* (from small subsistence to large producer, although medium producers feature slightly higher impacts than large ones), although yields per ha also increase along the same gradient (Fig. 2). This is due to the levels of intensification associated with the different producer types, which overcompensate for the economies of scale that are achieved. The per tonne weighted impacts of large and medium producers are slightly higher than those of small producers, implying that the high yields combined with intensification of the former do not represent an environmental benefit over the low yields and extensification of the latter. The single scores are dominated by climate change and land use. The impacts per ha are mainly on human health for large and medium producers (and for the national average) and on ecosystems for small producers (Supplementary Material).

When disaggregating production impacts only by *producing region*, it can be noticed that cocoa from Andean origin has lower impacts, both per ha and per t, than cocoa from other origins (Fig. 2). This is partly due to the absence of large commercial producers, and to the characteristics of Andean systems, which are generally extensive with low input intensities. When disaggregating impacts only by *cocoa variety*, impacts of CFA are considerably lower than those of CCN-51 only per *t*, but not per ha (Fig. 2).

Disaggregating results by *type of producer x cocoa variety*, the impacts per ha of cocoa of the large producers of CFA and CCN-51, as well as those of the medium producers of CCN-51, are considerably higher than those of the other combinations (Fig. 3). Climate negative emissions play a role on these differences, particularly for smallholders producing CCN-51, as the combination of very small inputs pressure and the accumulation of carbon in biomass contribute to larger climate negative emissions.

Further disaggregating by producing region (*type of producer x variety x region*), the impacts per kg of cocoa from large CFA producers on the Coast are considerably higher than for the other combinations (Fig. 4). This is due to the large contribution to the impacts of fertilisation (~45%) and irrigation (~25%) for CFA cocoa from large producers on the Coast. The net impact of CFA from medium-sized farmers in the Highlands is low, but the contribution of land use is very high (offset by C sequestration in biomass), due to the very low average yield of these farmers (0.07 $t{\cdot}ha^{-1}$, based on a sample of two farms, one of which is extensive). Apart from these exceptions, at this level of disaggregation (by type of producer, by variety and by region), there appear to be major differences across impacts, with certain combinations clearly underperforming (e.g. small producers' Amazonian CFA) as long as the particularities of these systems—i.e. multifunctional agroforestry systems—are not included in the assessment.

When disaggregating by *type of producer x variety x type of farming system* (monoculture, associated with other crops, agroforestry system), it is observed that there are large differences between the impacts per t of cocoa of different types of associations, which is due to the fact that, although relative yields do not vary, C sequestration in biomass varies significantly (i.e. it is much higher in agroforestry systems than in other associated systems) (Supplementary Material). In addition, impacts per ha of monoculture are systematically higher than those of associated systems, despite lower yields, due to the lower input intensity of systems in cultural association (Fig. 5).

The processing impacts (post-harvest, processing; Fig. 6) do not include the cocoa supply and the preceding processing steps. It is notable that thermal drying has higher impacts than solar drying, and that milk chocolate production has considerably higher impacts than the other types of chocolate, due to the impacts inherited from the other ingredients (milk powder, sugar).

If the impacts of chocolate production (including cocoa supply) are disaggregated by region, they do not vary by cocoa origin, except for chocolate based on Amazonian cocoa from agroforestry systems (Fig. 7). This is mainly due to the relative distances between production areas and Quito (the country's capital, located in the northern Highlands), where most (if not all) cocoa processors are located. Aggregated impacts (i.e. cocoa + transport + processing) vary, but C sequestration in biomass varies as well, generally in the same proportion, resulting in similar net impacts between origins, varieties, and producer types.

Table 2 Life cycle inventories of Ecuadorian cocoa farming; example of subsistence agricultural small producers, per ha per year

		CCN-51			CFA		
Items	Units per ha per year	Amazonia	Coast	Highlands	Amazonia	Coast	Highlands
Sample size	u	401	2046	701	114	917	76
LUC from oil palm	ha	0.01	0.07	0.01	0.01	0.07	0.01
C in cocoa tree biomass[a]	t CO_2	4.4 (3.3)	3.9 (4.0)	4.0 (3.7)	2.1 (4.6)	2.0 (2.5)	3.3 (4.6)
Additional C sequestered by associated (A) and agroforestry (AF) systems[b]	t CO_2				AF: 26.0 (28.2)	A: 4.2	AF: 15.4 (19.9)
Dry grain yield equivalent	t	0.24 (0.14)	0.53 (0.35)	0.48 (0.34)	0.22 (0.17)	0.19 (0.14)	0.21 (0.20)
Pruning (average of pruning types[c])	t	2.08 (1.28)	2.47 (1.70)	2.47 (2.08)	3.01 (3.01)	4.37 (4.92)	4.37 (4.70)
Harvest residues (empty cob: ~ 68%[d])	t	0.70 (0.41)	1.57 (1.04)	1.43 (1.02)	0.64 (0.51)	0.58 (0.42)	0.61 (0.58)
Total biomass contributed to the soil	t	2.78 (1.69)	4.04 (2.73)	3.90 (3.10)	3.65 (3.52)	4.95 (5.34)	4.99 (5.29)
Crop density	u	714 (625)	909 (1111)	833 (909)	714 (625)	769 (769)	714 (625)
Irrigation[e]	ha	0.002	0.286	0.106	0.009	0.077	0.053
Mechanised pruning (motor mower)	hr	1.90	1.87	2.00	1.31	1.40	1.63
Mechanised weeding	hr	8.14	8.14	8.14	8.14	8.14	8.14
Pesticide application (portable sprayer)	hr	2.54 (0)	2.16 (0)	2.06 (0)	1.88 (0)	0.56 (0)	1.29 (0)
Fertilisation – solids	hr	5.42 (0)	14.20 (0)	22.39 (0)	1.72 (0)	3.24 (0)	19.44 (0)
Fertilisation – liquids	hr	0.01 (0)	0.03 (0)	0.05 (0)	0 (0)	0.05 (0)	0.05 (0)
Manure	kg	7.78 (0)	2.05 (0)	72.71 (0)	0.44 (0)	4.66 (0)	81.33 (0)
Fermented organics	kg	1.36 (0)	1.46 (0)	17.05 (0)	0.97 (0)	0.54 (0)	3.22 (0)
Liquid organics	kg	0.06 (0)	0.19 (0)	0.31 (0)	0.002 (0)	0.30 (0)	0.30 (0)
NPK	kg	20.17 (0)	62.22 (0)	35.40 (0)	7.29 (0)	10.92 (0)	30.11 (0)
N	kg	2.44 (0)	15.78 (0)	6.33 (0)	1.59 (0)	3.18 (0)	1.99 (0)
P	kg	0.60 (0)	0.24 (0)	2.20 (0)	0 (0)	0 (0)	0 (0)
K	kg	0.19 (0)	3.44 (0)	0.63 (0)	0 (0)	0.12 (0)	0.01 (0)
Organic pesticides	kg	0.08 (0)	0.04 (0)	0.05 (0)	0 (0)	0.02 (0)	0 (0)
Chemical herbicide	kg	0.79 (0)	0.78 (0)	0.62 (0)	0.63 (0)	0.20 (0)	0.31 (0)
Chemical insecticide	kg	0.39 (0)	0.35 (0)	0.29 (0)	0.45 (0)	0.08 (0)	0.28 (0)
Chemical fungicide	kg	0.26 (0)	0.12 (0)	0.26 (0)	0.04 (0)	0.04 (0)	0.19 (0)
Other chemical pesticides	kg	0.001 (0)	0.01 (0)	0.01 (0)	0.004 (0)	0.002 (0)	0.001 (0)
N in mineral fertilisers	kg	5.47 (0)	25.11 (0)	11.64 (0)	2.69 (0)	4.82 (0)	6.50 (0)
N in organic fertilisers	kg	0.05 (0)	0.02 (0)	0.48 (0)	0.01 (0)	0.03 (0)	0.42 (0)

Table 2 (continued)

		CCN-51			CFA		
Items	Units per ha per year	Amazonia	Coast	Highlands	Amazonia	Coast	Highlands
Total N inputs (from mineral and organic fertilisers and crop residues)	kg	56.85 (31.33)	96.14 (48.24)	81.24 (55.68)	71.78 (67.28)	100.25 (104.12)	102.83 (102.10)
Nitrates: IPCC 2019, without irrigation	kg NO_3-N	1.32 (0)	6.03 (0)	2.91 (0)	0.65 (0)	1.16 (0)	1.66 (0)
Nitrates: IPCC 2019, with irrigation	kg NO_3-N	0.003 (0)	1.73 (0)	0.31 (0)	0.01 (0)	0.09 (0)	0.09 (0)
Ammonia	kg NH_3-N	1.18 (0)	4.86 (0)	2.46 (0)	0.53 (0)	0.92 (0)	1.60 (0)
Nitrous oxide	kg N_2O-N	0.70 (0.38)	1.20 (0.59)	1.01 (0.68)	0.88 (0.82)	1.23 (1.28)	1.27 (1.25)
Nitrogen oxides	kg NOx-N	0.15 (0.08)	0.25 (0.12)	0.21 (0.14)	0.19 (0.17)	0.26 (0.27)	0.27 (0.26)

Main source: ESPAC 2019. Additional sources and notes: [a](GIZ 2011; Fischer 2018; Galarza Ferrín 2019), [b](Torres et al. 2014; Schneidewind et al. 2019), [c](Engracia Manobanda 2018), [d](Martínez-Ángel et al. 2015; Estrada León 2018), [e]Furrow irrigation: 33%, sprinkler irrigation: 35%, micro-sprinkler irrigation: 21%, drip irrigation: 3%, other system: 8%

Table 3 Life cycle inventories of Ecuadorian cocoa post-harvest in collection centres, per t of product (fermented and dried beans)

Items	Units per t	Quality-oriented post-harvest with solar drying	Volume-oriented post-harvest with thermal drying
Area intervened with infrastructure	m^2	1.40E-3	1.40E-3
Plastic tunnel	m^2	1.19E-2	
Wooden crates	m^3	5.00E-5	
Plastic bags (15 kg)	u		5.51
Wooden drawers	m^3	2.75E-4	
Electricity	kWh	76.41	76.41
Gas	MJ		1.07E3
Diesel	MJ		1.30E3
Petrol/gasoline for transport	kg	4.59	4.59
Pallets	u	2.5E-2	2.5E-2
Plastic barrels	u	0.05	0.05
Scales	u	0.01	0.01
Raw material: wet cocoa beans	t	2.75	2.75
By-product: mucilage	t	1.75	1.75

Notes: Infrastructure is allocated considering a lifespan of 20 years (buildings), 2 years (plastic tunnel, crates, and other containers), and 5 years (drawers), and an annual processing capacity of 1000 t

Table 4 Life cycle inventories of Ecuadorian industrial cocoa processing systems t of product

Items	Units per t	Primary processing	Secondary processing
Industrial infrastructure	p	1.00E-4	2.00E-3
Electricity	kWh	3510	3134
Raw material: fermented and dried cocoa beans	t	1.20	
Raw material: products from primary processing	t		0.40–0.86
Raw material: sugar, milk powder	t		0.14–0.60
Packaging materials: cardboard, aluminium foil	kg		136
Waste: shells	t	0.11	

Notes: see Table 1 for the specific proportions of raw materials in secondary processing, per type of product

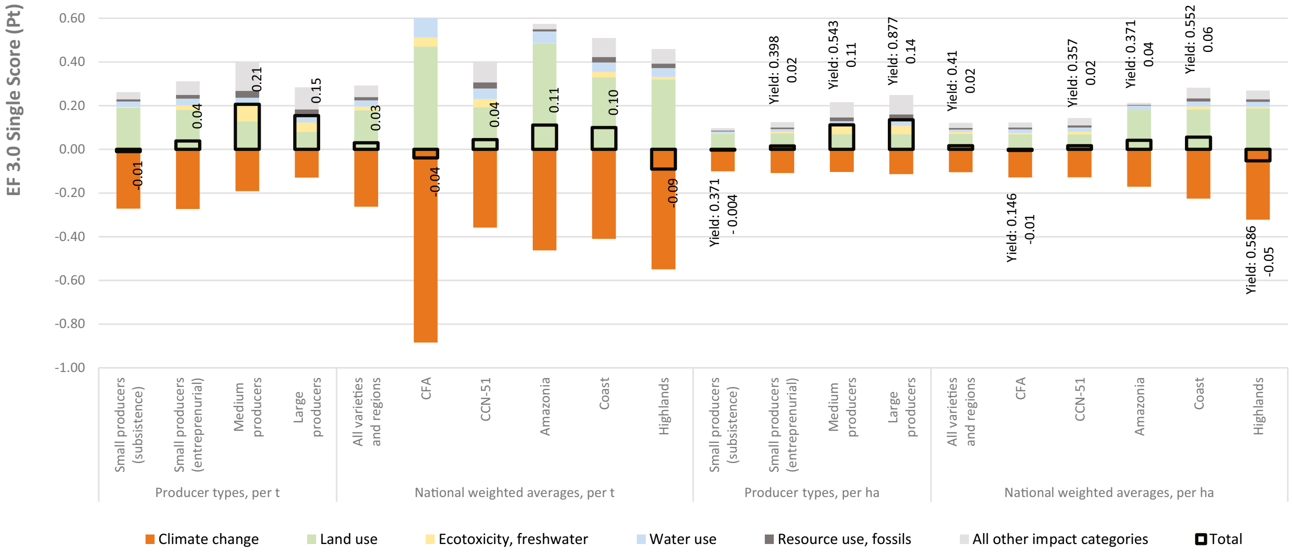

Fig. 2 Cocoa production, by type of producer and national averages (weighted by variety, by region of origin and at the national level); per t dry bean equivalent [EF 3.0 single score by impact categories]

A contribution analysis identifies the dominant sources of impacts and their relative importance by producer type, including production-weighted national average tonne of dry beans and hectare of cocoa plantation (Fig. 8):

- Irrigation is the single top contributing factor, followed in importance by the provision of infrastructure (which includes machinery and materials), of energy (transport, farm labour, energy embedded in industrial inputs) and of K-fertilisers, led by small entrepreneurial producers. Negative emissions associated with climate change play a key role in balancing and even over-compensating the impacts of the single score (Fig. 8a).
- For the small subsistence producers, the contribution of energy consumption and irrigation is less representative, yet irrigation remains is the main contributing factor, as well as negative direct emissions from both CCN-51 and CFA systems, but chiefly from CCN-51 (Fig. 8b).

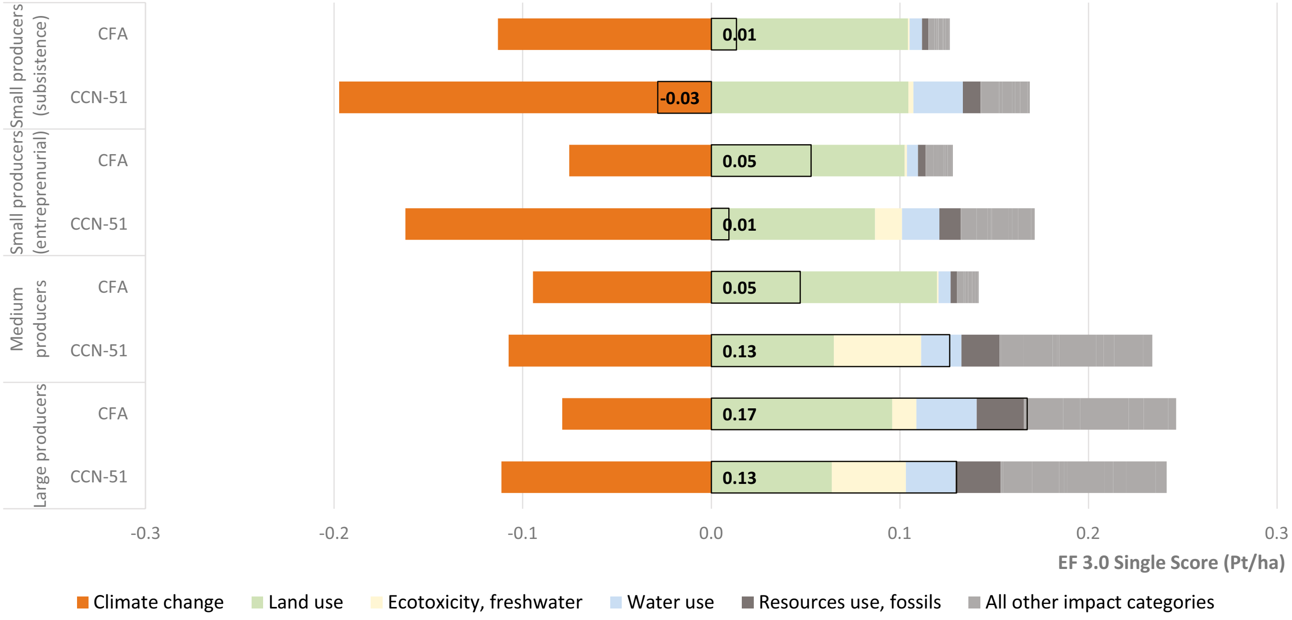

Fig. 3 Cocoa production, by type of producer and variety; per ha [EF 3.0 single score by impact category]

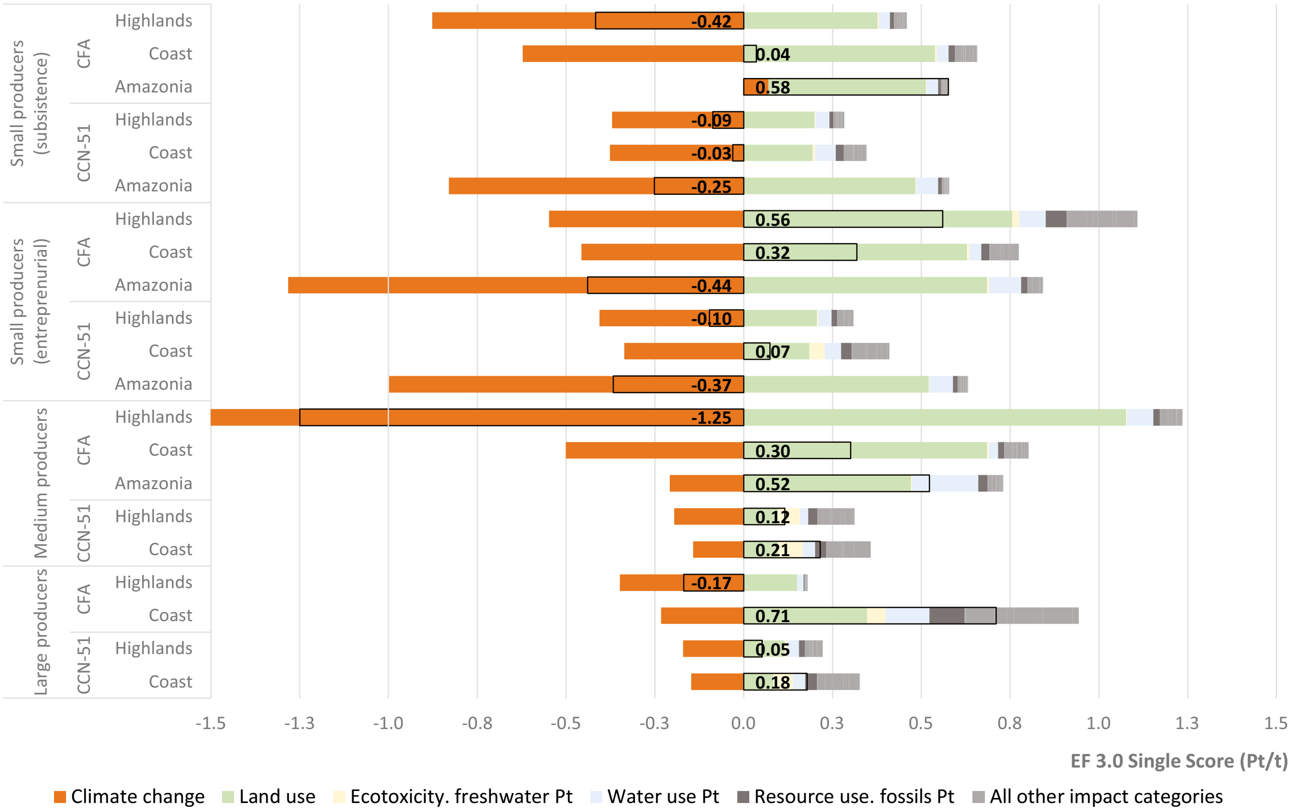

Fig. 4 Cocoa production, by type of producer, variety and region of origin; per t dry bean equivalent [EF 3.0 single score by impact category]

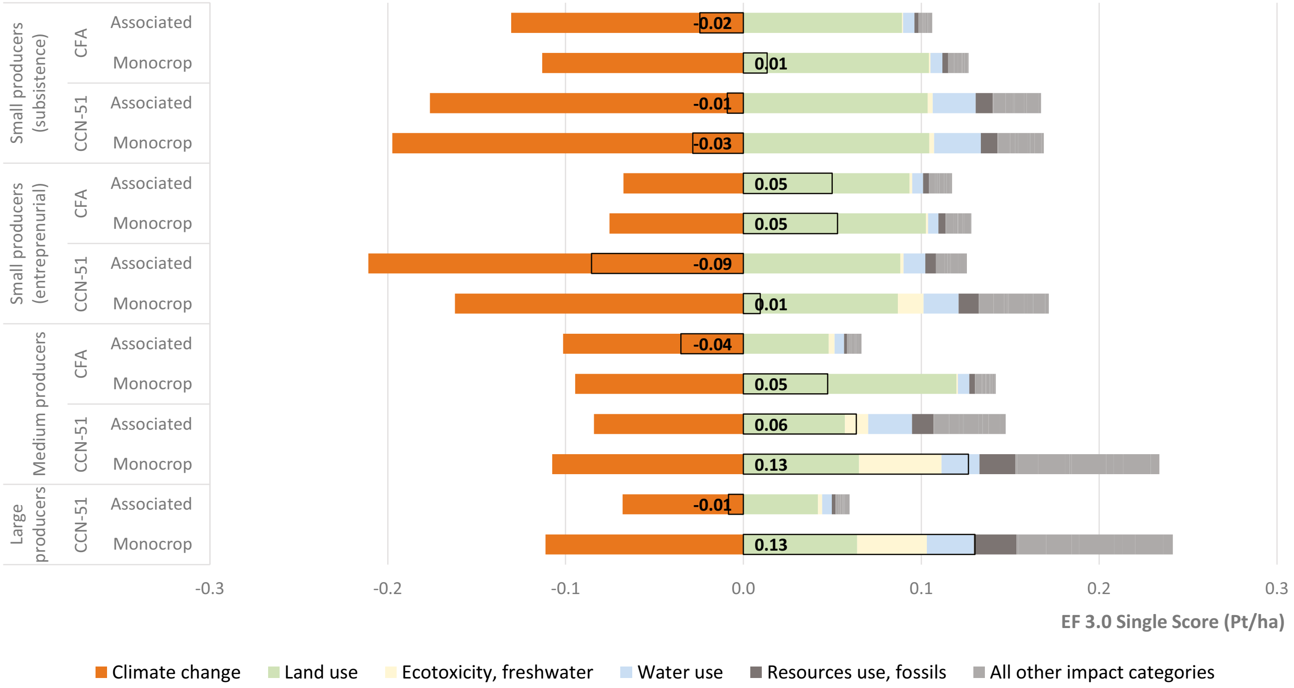

Fig. 5 Cocoa production (monoculture vs. associated systems), by type of producer and variety; per ha [EF 3.0 single score by impact category]

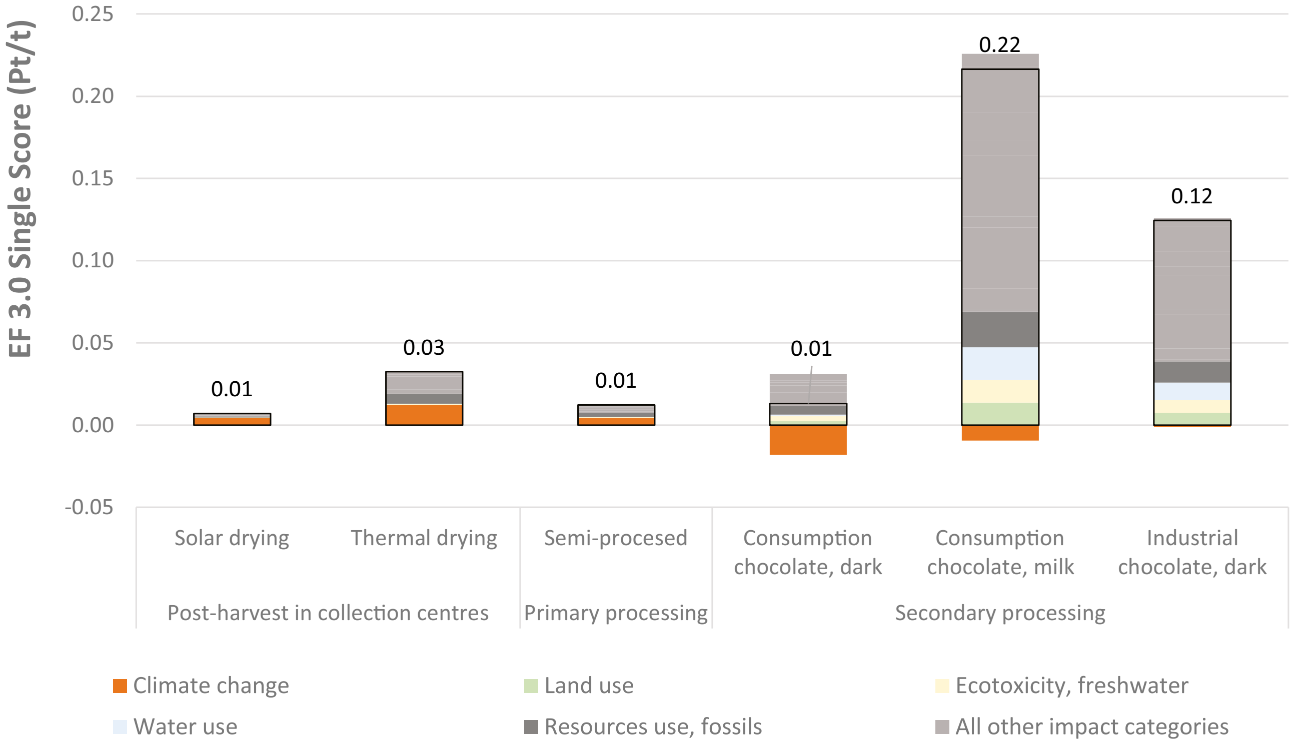

Fig. 6 Post-harvest and processing activities (semi-processed and chocolate); by t of product [EF 3.0 single score by impact category]

- The contribution of these factors increases along the large-medium-smallholder axis (Fig. 8c).

The impacts of the sub-chains are ordered, from highest to lowest, as: Quality > Premium > Organic > Volume > Semi-processed (Fig. 9). This is mainly due to the differences in yields and negative direct field emissions among the different types of producer and cocoa varieties that feed the sub-chains. Transport contributes marginally to the impacts, as does primary processing in the case of the semi-processed sub-chain.

The identified sub-chains have different impact intensities, due to differences in yields between the different types

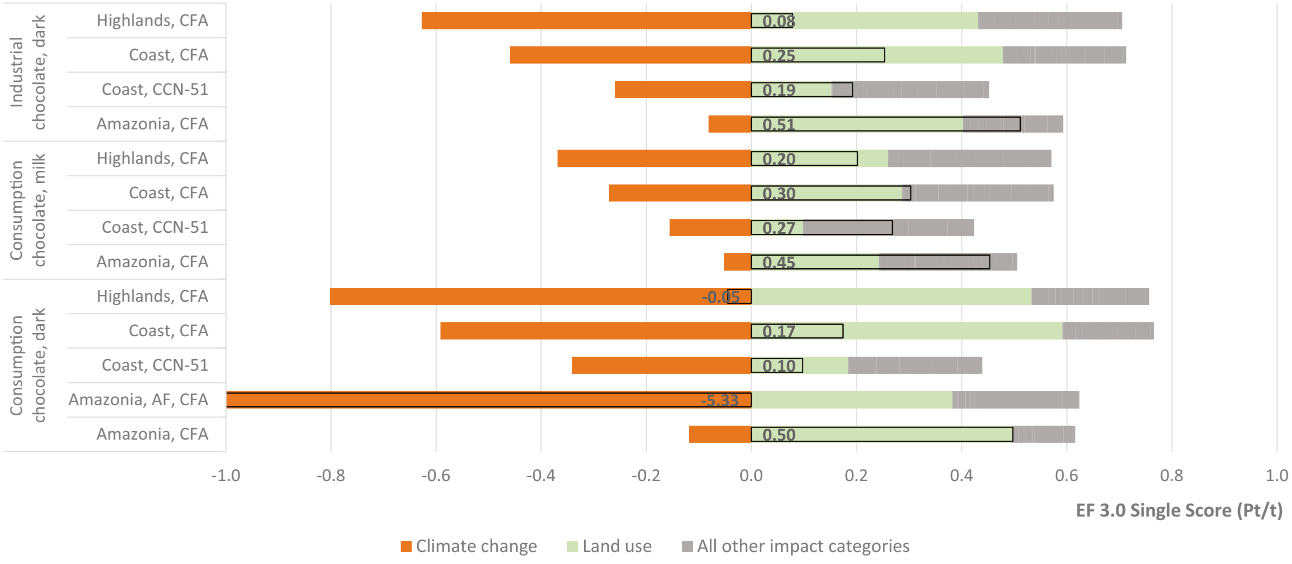

Fig. 7 Chocolate by type, by region of origin and cocoa variety; by t of product [EF 3.0 single score by impact category]

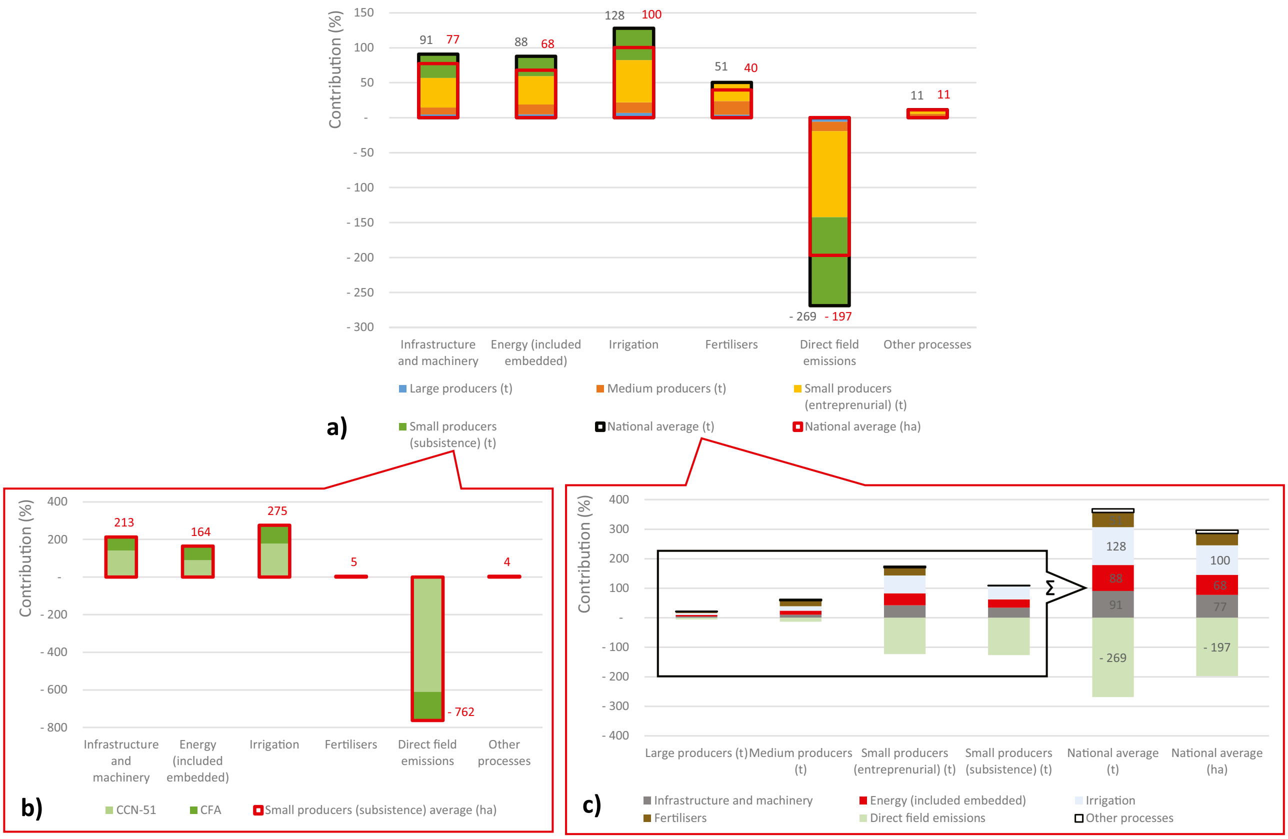

Fig. 8 Contribution analysis of cocoa production, by type of producer: **a** contribution of factors per producer type to the national average, **b** contribution of varieties to the average of small subsistence producers, and **c** contribution of producer types to the national average [EF 3.0 single score]

of cocoa producers and varieties that feed the sub-chains. Transport contributes marginally to the impacts, as does primary processing in the case of the semi-processed products sub-chain.

All disaggregated midpoint results are included in the Supplementary Material.

3.3 Sensitivity and variability

The choice of median over mean values when building inventories has a noticeable effect on impact results (Fig. 10). Means-based impacts are considerably higher, but less representative of the actual practices of cocoa producers.

The variability of impacts associated with the variability of key contributing factors defining each combination of producer type, region, and variety—yield, intensity of fertiliser and plant protection product use, and even the method of calculating direct emissions—was explored. Pairwise comparisons, propagating uncertainty with Monte Carlo (1000 runs, 95% confidence), indicate, for example, that:

- 100% of the time, the (single score) impacts per ha of large producers (0.88 t·ha^{-1}) are greater than those of smallholder subsistence producers (0.37 t·ha^{-1}); i.e. the apparent differences between the impacts of these two productions (see Fig. 2) are significant. Only for climate change, 82% of the time the impacts of large producers are smaller than those of smallholder subsistence producers.
- 91% of the time, the impacts per t of Amazonian production are lower than those of coastal production; i.e. the apparent differences between the impacts of these two productions (see Fig. 4) are barely significant. Only in the case of water use and land use, the relation between the two systems is inverse.
- 100% of the time, the impacts per t of Amazonian CFA production in agroforestry systems are less than those of Amazonian CFA production in monoculture (in both cases, by small subsistence farmers); results driven uniquely by climate change (for all other impact categories contributing to the single score, the relation is inverse). A similar comparison, per ha, between subsist-

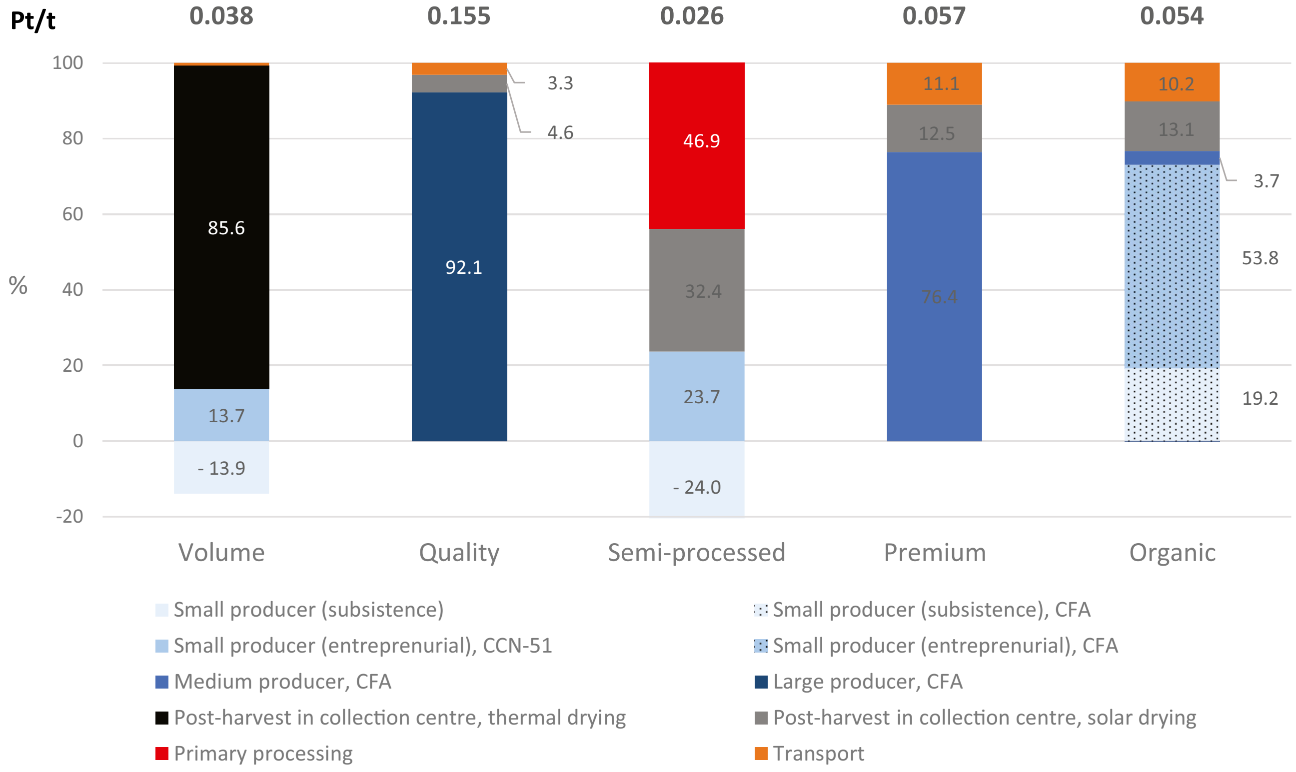

Fig. 9 Cumulative sub-chain impacts (Pt·t^{-}.^{1}) and contribution analysis, for products exported from the port of Guayaquil [EF 3.0 single score]

ence smallholders growing CFA in cultural association vs. CCN-51 in monoculture, shows that 94% of the time the impacts of the former are lower than those of the latter. These comparisons demonstrate that the apparent differences between the impacts of these systems (see Fig. 5) are significant.

- 72% of the time, the impacts per t of the volume sub-chain are lower than those of the quality sub-chain (i.e. a barely significant difference), while 74% of the time, the impacts per t of the premium sub-chain are less than those of the organic sub-chain (i.e. a significant difference).

The variability observed across systems is large and must be considered for comparisons to be meaningful. Impacts are highly sensitive to yield and the amount of C sequestration in biomass (which is a function of variety, type of system, type of cultural association, and age of the plantation).

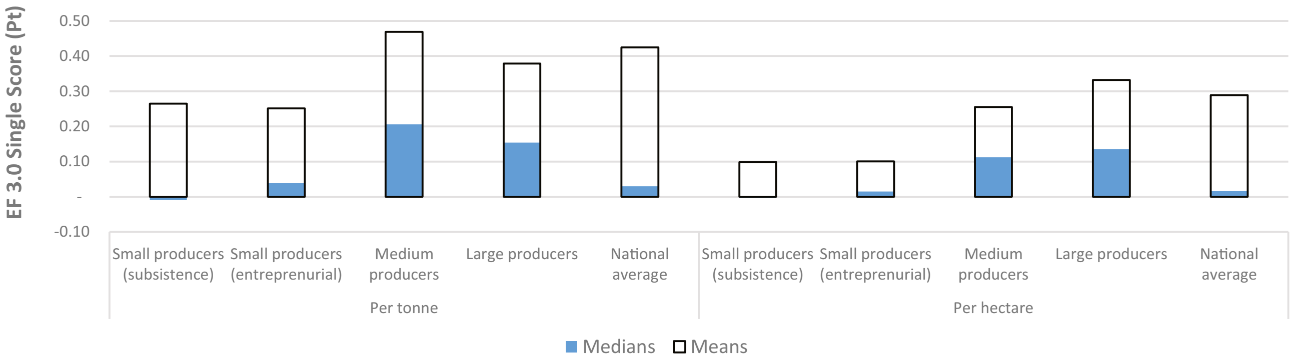

Fig. 10 Cocoa production, by type of producer and national weighted averages (dominated by smallholders' production) [EF 3.0 single score by impact categories], comparison of impacts based on mean and median values

Table 5 Comparison of the midpoint climate change impact (kg $CO_2 \cdot t^{-1}$) of dry bean production among different cocoa exporting countries [the first value corresponds to the modified EF 3.0, the second to the original **EF 3.0]**

Source	Product	Brazil	Côte d'Ivoire	Cameroon	Ecuador	Ghana	Indonesia
WFLDB (Nemecek et al. 2020)	Dry beans, from agroforestry systems	– 3566 – 1672	26 999 28 911	16 868 18 782	– 3 509 – 1614	6 122 8 018	36 697 38 608
	Dry beans, from intensive systems	556 2 456			287 2 178		14 637 16 549
	Dry beans, from improved practices systems		20 451 22 351	13 382 15 282		6 250 8 139	
	Dry beans, from extensive systems		29 186 31 094	19 405 21 313		8 483 10 377	
	Dry beans, from semi-intensive systems	675 2 600			713 2 638		29 511 31 453
	Dry beans, national average	– 294 1617	27 263 29 172	17 562 19 474	– 61 1848	7 075 8 968	25 004 26 928
ecoinvent (Wernet et al. 2016)	Dry beans, national average		8 909 10 802			14 103 16 011	40 413 42 338
This study	Commodity beans, small producers				– 14 887 3 222		
	Differentiated beans, large producers				– 3 241 2 718		
	Premium beans, medium producers				– 6 458 2 521		
	Organic beans, small producers				– 9 957 2 788		

Notes: All values were computed from datasets available in the referenced databases, and accessed through SimaPro

Monte Carlo uncertainty propagation did not consider the biodiversity impact category, as it is not included in EF v3.0, and thus was computed separately. All described Monte Carlo results are presented in the Supplementary Material.

3.4 Comparison with other world cocoa value chains

Using the modified EF 3.0 method, the impacts of dry grain and chocolate from Ecuador were compared with equivalent processes available in ecoinvent, WFLDB and AGRIBALYSE, in terms of climate change (Tables 5 and 6). It is observed that the impacts of Ecuadorian beans are comparable to those of Brazil, and the impacts of both countries are considerably lower than those of the other exporting countries. The reasons are multiple, and include pressure on water use, and relative phytosanitary, fertilisation, and transport intensities, as well as energy use intensity and origin (i.e. nature of the energy mix) across origins, especially for chocolate products.

Land conversion plays a dominant role: for example, in Côte d'Ivoire's systems, land conversion accounts for > 90% of climate change impacts, while in Ecuador, because cocoa has been planted for more than 20 years in disturbed areas, the net sequestration of C in biomass is so significant that climate change impacts are low or negative (Table 7).

Ecuadorian yields have increased in recent years compared to the world average (Supplementary Material). The increase in cocoa production in Ecuador, and more generally in the Americas, follows a different strategy than in other continents (yield improvement vs. area expansion). It has been observed that Africa, the main cocoa producing continent in the world, increases its production by incorporating 1.23 million ha, with increases of less than 5% in yields ($t \cdot ha^{-1}$), while Asia reduces its share in world production by 97 000 t, despite incorporating more than one million new hectares to production. In the other hand, the countries of the Americas increase their production through productivity increases of 84.2% and the incorporation of 124 000 ha of new production (representing an 8% increase in the area sown), in a more sustainable model than that used by the other continents (Arvelo Sánchez et al. 2017).

3.5 Carbon sequestration (climate change)

Carbon sequestration in agricultural systems, which takes place in plant biomass and soil organic carbon (SOC), is a function of several parameters: amount and permanence of biomass (above and below ground), amount and frequency of organic matter inputs, pedoclimatic conditions, and other agricultural practices (e.g. soil tillage, irrigation). The history of each agricultural plot is also a determinant of the

Table 6 Comparison of the midpoint climate change impact (kg $CO_2 \cdot t^{-1}$) of the production of different dark chocolates by origin of beans [the first value corresponds to the modified EF 3.0, the second to the original EF 3.0, except where otherwise indicated]

Source	Product	Ecuador	Ghana	Indonesia	Peru	N/A
This study	Average of systems, Amazonia, CFA	−4.57 3.78				
	Agroforestry system, Amazonia, CFA	−229 1.81				
	Average of systems, Coast, CCN-51	−13.14 3.34				
	Average of systems, Coast, CFA	−22.76 6.40				
	Average of systems, Highlands, CFA	−30.82 6.49				
(Bianchi et al. 2020) [a]	National average, small producers	1.51	1.25			
	Traditional monocrop			3.10		
	Agroforestry system			2.00		
(Pérez Neira 2016) [b]	National average (traditional, technified)	2.57				
(Recanati et al. 2018) [c]	National average				2.62	
AGRIBALYSE (Asselin-Balençon et al. 2020)	Undetermined					10.92 17.44
WFLDB (Nemecek et al. 2020)	Undetermined					13.65 16.30

Notes: [a]Method unstated, but presumably IPCC 2013 GWP 100a (http://www.climatechange2013.org), [b]CO_2-eq emissions were estimated from non-renewable energy consumption and emission factors from the literature, [c]CML-IA 2001 Method (Guinée et al. 2001)

impact on climate change, especially with regard to land use change (LUC), which is analysed in LCA over the last 20 years (e.g. Table 8). The underlying logic is that a change of land use from a more natural to a less natural environment (e.g. from forest to agricultural system; from agroforestry agricultural system to monoculture agricultural system) implies a loss of C (Brandão and Milà i Canals 2013; Koellner et al. 2013). The impact category LUC captures such dynamics, and there is even talk of "indirect LUC", i.e. the indirect consequences on LUC dynamics in one system due to changes in another, albeit the validity/relevance of the concept is non-consensual (Finkbeiner 2013; Marvuglia et al. 2013). In the case of cocoa, for instance, a change in demand (from companies operating in Ecuador or from international markets) could imply additional LUC (e.g. deforestation or crop substitution). The exploration of such phenomena is part of the so-called consequential LCA (Zamagni et al. 2012); not adopted in this work.

In general, perennial systems sequester more carbon than annual systems, due to the persistence of the biomass and protection of the soil from erosion. For Ecuador, an aerial biomass accumulation curve (average between CCN-51 and CFA, Supplementary Material) was determined, from which the amount of C sequestered by cocoa plants in monoculture was derived.

The estimations of biomass and residual biomass accumulation for each type of system are summarised in Table 8.

The results (Supplementary Material) suggest a more interesting SOC sequestration potential in the CCN-51 systems than in the CFA systems (in terms of the respective annual sequestration rates), on the Coast. In the Highlands, CFA sequestration rates are higher than those of CCN-51. In Amazonia, too, sequestration rates are higher for CFA (especially in agroforestry systems) than for CCN-51, but in both cases, these rates are generally negative; i.e. there is a net loss of SOC. For Amazonian agroforestry systems, and only on Acrisol soil (among the different predominant soil types), sequestration

Table 7 Comparative estimated midpoint impact on climate change (kg $CO_2 \cdot ha^{-1}$) due to land use change among different cocoa exporting countries [the first value corresponds to the modified EF 3.0, the second to the original EF 3.0]

Impact of land use change (mainly due to deforestation)	Brazil	Côte d'Ivoire	Cameroon	Ecuador	Ghana	Indonesia
Global warming potential associated with land use change annualised over 20 years	23 486 23 495	35 473 35 487	20 636 20 645	83.4 84.4	15 786 15 793	28 781 28 792

Source: WFLDB (Nemecek et al. 2020)

Table 8 Biomass and residual biomass accumulation by type of cocoa system (i.e. producer) in Ecuador

Systems	Types	Computation	Sources	t CO$_2$·ha^{-1}·y^{-1}
All CCN-51, monocrop CFA and non-agroforestry associated CFA systems	CCN-51: all types Monocrop CFA: all types	Total biomass accumulation/system age (cocoa only)	(GIZ 2011; Fischer 2018; Galarza Ferrín 2019)	~2.9[a]
	Associated CFA: medium and large types	Total biomass accumulation: other crops, grasses, biomass residues	(Schneidewind et al. 2019)	4.23
Amazonia agroforestry CFA systems	Small type	Total biomass accumulation/system age (cocoa + other trees)	(Torres et al. 2014)	25.99
Highlands agroforestry CFA systems	Small type	Total biomass accumulation/system age (cocoa + other trees)	(Schneidewind et al. 2019)	15.35

[a] See biomass accumulation curve (Supplementary Material): biomass accumulation plateau from ~ 12 years at ~ 35 t DM/ha

rates of between 0.31 and 0.35 t·ha^{-1}·year^{-1} were estimated. In contrast, Torres et al. (2014) suggest annual sequestration rates of 1.8 for CCN-51 and 0.47 for agroforestry CFA, but the authors did not indicate the soil type used in their calculations.[1] Cerri et al. (2006) report an annual SOC sequestration in Amazonian agroforestry systems of 0.83 t·ha^{-1}.

Only on the Coast, especially in drier areas, the net SOC (i.e. SOC at the end of the simulation minus total erosion) is positive, probably due to the intensity of rainfall erosion in the Highlands and in Amazonia. No estimate of SOC sequestration is sufficiently informative unless erosion is considered (Albers et al. 2022).

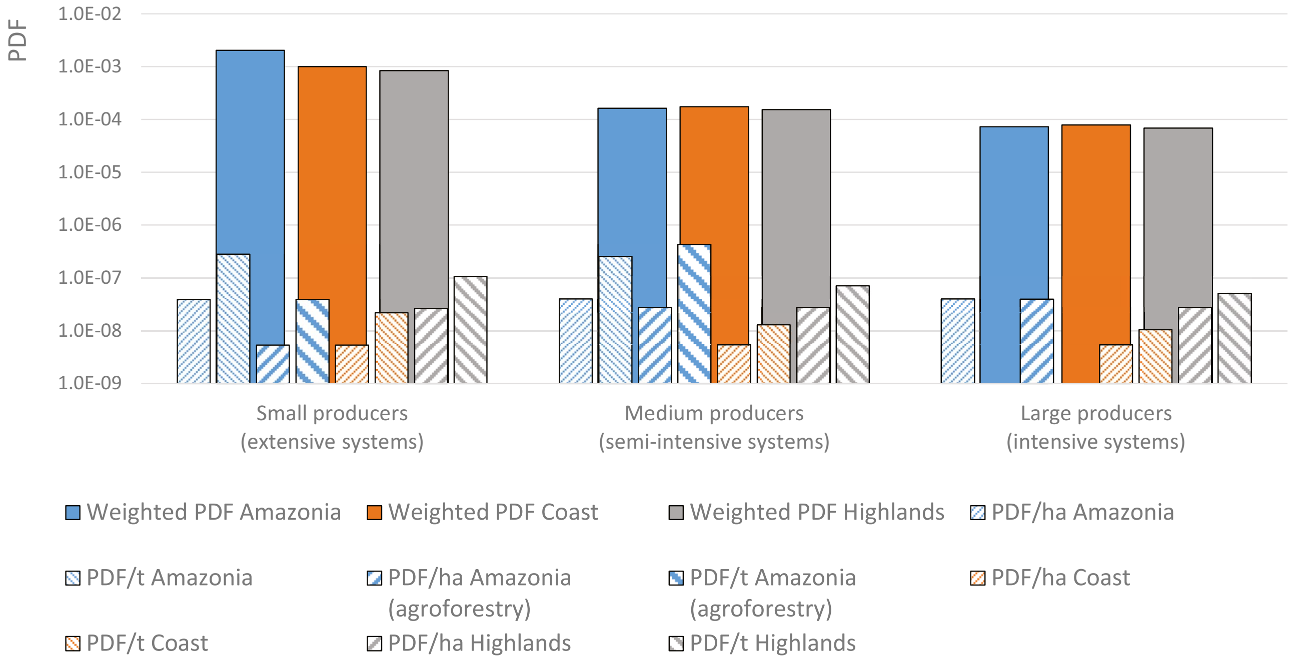

Fig. 11 Potential disappeared fraction of species by type of producer and by region, weighted by Ecuadorian cocoa area [per ha and per t]

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[1] Torres et al. (2014) identify a total SOC sequestration of 74.9 t C·ha^{-1} for Amazonian cocoa systems in monoculture (age: 5 years, tree cover: 4%) and 69.2 t C·ha^{-1} for agroforestry systems (chakra, age: 7 years, tree cover: 40.6%), i.e. an annual sequestration of 1.8 and 0.47 t·ha^{-1}, respectively, based on a SOC content in the jungle soil of 65.9 t·ha^{-1}.

3.6 Biodiversity

Agricultural expansion and other activities (mining, oil extraction, urban expansion) contribute to deforestation and environmental degradation in Ecuador. For example, in the period 1990–2000, 74 000 ha of forest were converted to other land uses annually (Cuesta et al. 2013). In the period 2008–2014, deforestation reached 47 500 ha per year (MAE 2015).

Monoculture agricultural production contributes to environmental degradation, including loss of biodiversity (Bonilla et al. 2016). This is particularly dangerous in the Amazonia, which has an extremely diverse and fragile ecosystem. In this region, the expansion of the agricultural frontier has historically been associated with colonisation (sometimes sanctioned by the state), extractive activities (oil, timber), and the expansion of the agricultural frontier (Viteri-Salazar and Toledo 2020) (Supplementary Material). In the Amazonia, there are already areas of overlap between different types of cocoa systems and protected areas. Nevertheless, native communities that produce via agroforestry systems (e.g. chakra system (Torres et al. 2014; Coq-Huelva et al. 2017)) are key actors for the preservation of natural and cultivated biodiversity.

The Ecuadorian ecoregions are Eastern Cordillera real montane forests (Highlands), Napo moist forests (Amazonia), and Western Ecuador moist forests (Coast). The corresponding characterisation factors are listed in the Supplementary Material. The impacts weighted by the different regional areas occupied by the different types of producers are presented in Fig. 11. It can be seen that, as the vast majority of the cocoa area is occupied by smallholders, their contribution to species loss is dominant, although these systems present a lower risk per ha. On the other hand, the potential impacts per ha are lower on the coast than in the highlands or Amazonia, largely due to the relative number of species between these regions.

4 Conclusions

The vast majority of the volume of cocoa produced in Ecuador is due to smallholders, and therefore, environmental initiatives should focus on these producers, mainly on improving their yields. Such initiatives do not necessarily imply intensification of production, as it was observed that, although medium and large (intensive) producers generate slightly larger impacts per ha as small (extensive) producers, their impacts per *t* are much higher. Initiatives focusing on medium/large producers should aim at improving economies of scale (or other mechanisms enabling lowering inputs or increasing negative direct field emissions, especially those leading to climate change mitigation), to reduce their impacts per *t*.

The semi-processed and volume sub-chains, based on small producers growing mainly CCN-51, seem to be the most sustainable. When mean values are retained instead of medians, the organic and premium sub-chains (based, respectively, on small and medium producers growing CFA) rank as the most sustainable. More detailed primary data-based assessments are needed to fully understand the relative impacts of these sub-chains, as the statistically based approach relying on virtual representative inventories (Avadí et al. 2016) does not paint a clear enough picture.

The differences between agroforestry systems (especially Amazonian) and monoculture are non-negligible, and even more so if biodiversity and carbon sequestration in perennial biomass (not in SOC) are taken into account: agroforestry systems (and associated systems in general) are more environmentally sustainable, but multifunctional assessments are needed to better understand the extent of their sustainability.

In Ecuador, cocoa systems contribute greatly to climate change mitigation thanks to the large amount of carbon they sequester in biomass, and since they are perennial systems, this sequestration is long-lasting (unlike annual crops). As cocoa systems do not seem to contribute to deforestation, their net C balance is very competitive compared to systems in other regions.

The impacts of Ecuadorian cocoa, at least pertaining to the impact category climate change, are considerably lower than those of products from other international cocoa value chains, as demonstrated by a comparison of the climate change impacts of cocoa beans and chocolate from different exporting countries (Avadí et al. 2021). When the impacts are expressed in terms of single scores, climate change overcompensates all other impact categories, which may induce the potentially biased interpretation that all impacts are lower than those of other cocoa value chains. Nonetheless, the Ecuadorian value chain's agricultural phase generally exhibits low input pressure (except for large intensified producers, especially CCN-51), contributes to climate change mitigation through high C sequestration in biomass that exceeds C losses due to land use change (e.g. deforestation), and does not seem to pose an immediate threat to biodiversity. A recent estimate of the impact of land use change associated with cocoa in Ecuador indicates that deforestation is minimal in the cocoa context compared to other countries (Table 7). In the Amazonia, there are already areas of overlap between different types of cocoa systems and protected areas. Nevertheless, native communities that produce via agroforestry systems (e.g. Chakra) are key actors for the preservation of natural and cultivated biodiversity.

Finally, the robustness of this study could be questioned, as it was demonstrated that different relative results (i.e. regarding the relative impact intensity across system types) can be obtained depending on the central tendency units chosen (medians, means), which is a common trend in statistics-based analyses of biological systems (Cardinal 2015). Further statistical analyses should be carried out, but such endeavour exceeds the scope of this article.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-023-02142-4.

Acknowledgements The author was founded by the VCA4D — Value Chain Analysis for Development 2016-2022 programme (https://europa.eu/capacity4dev/value-chain-analysis-for-development-vca4d-), through grant agreement 2016/375-804. The author acknowledges the contribution of various institutions and individuals to this work: the project management unit in Brussels, the European Delegation in Ecuador, and the national stakeholders and institutions who kindly provided data. The author particularly thanks his project team: Ludovic Temple (CIRAD), Vinicio Salgado (OCE), and Johan Blockeel (FIBL). The project team collaboratively performed the functional analysis on which this LCA study was based.

Data availability All data generated or analysed during this study are included in this published article and its Supplementary Material. The raw data are available from the corresponding author on reasonable request.

Declarations

Competing interests The author declares no competing interests.

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