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# Assessment of the environmental impact and economic performance of cacao agroforestry systems in the Ecuadorian Amazon region: An LCA approach

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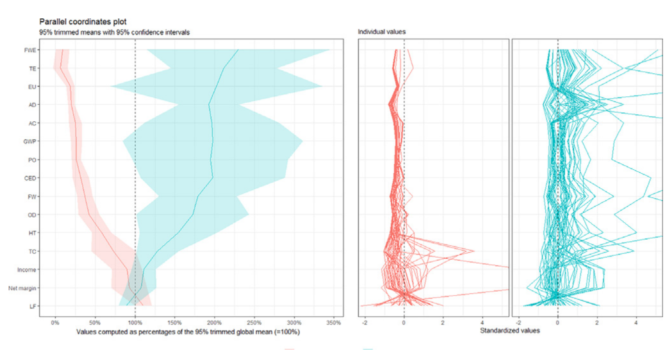
## HIGHLIGHTS

- The environmental performance of cacao production was assessed applying LCA.
- Organic management reduces all the environmental impacts except for land footprint.
- Organic management also improves economic/environmental efficiency.
- Economic profitability is one of the weaknesses of cacao production in this region.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Ecuador is the third largest cacao exporter in the world. Up to 10 % of Ecuador's cacao production is grown in the Amazon region, mostly under conventional (CA) and organic (OA) agroforestry systems. Despite the importance of cacao in this area, no previous studies on its environmental impact and economic viability have yet been carried out. The main objective of this research is to fill this gap and, more specifically, perform a comparative analysis between CA and OA systems. For this purpose, primary information was gathered from 90 farms (44 conventional and 46 organic ones) that implement land management practices. The environmental performance of cacao production was assessed using a life cycle analysis methodology, with a cradle-to-farm gate approach. Up to twelve impact categories and five environmental and monetary efficiency indicators were estimated based on three functional units (1 kg of cacao, 1 kg of output sold, and 1 ha). Additionally, an economic viability analysis was performed, focused on profitability. The results show that organic management allows to reduce the environmental impact in all the analyzed categories, except for the land footprint, and improved the environmental and economic efficiency of agroforestry systems. The economic analysis shows no statistically significant differences between CA and OA profitability (net margin), which can be improved by selling co-products. Despite the low environmental impact of both types of system, economic profitability is

*Abbreviations:* AC, Acidification; AD, Abiotic depletion; CA, Conventional agroforestry systems; CED, Non-renewable cumulative energy demand; EcoROI, Economic return on investment; EI, Energy intensity; EROI, Non-renewable Energy return on investment; EROWI, Energy return on water investment; EU, Eutrophication; FEW, Freshwater ecotoxicity; GHG, Greenhouse gas; GHG I, Greenhouse gas emission intensity; GWP, Global warming potential; HT, Human toxicity; LCA, Life cycle assessment; LF, Land footprint; OA, Organic agroforestry systems; OD, Ozone layer depletion; PO, Photochemical oxidation; TC, Total cost; TE, Terrestrial ecotoxicity; WF, Water footprint.

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certainly one of the weaknesses of cacao production in the Ecuadorian Amazon region. This study contributes to develop technical, production-related and political actions that could improve the economic cacao production situation without jeopardizing the environmental benefit obtained by these systems.

## 1. Introduction

Cacao is a globalized good with a growing demand in recent years. Ecuador is the third largest cacao exporting country in the world (7.9 % of cacao beans) (Faostat, 2022). This activity accounts for approximately 15 % of the country's peasant economy (Anecacao, 2022). Ecuador's Amazon region, which comprises the provinces of Sucumbíos, Orellana, Napo, Pastaza, Morona Santiago and Zamora Chinchipe, produces 10 % of the cacao grown in the country. This represents >315,000 tons of cacao beans, which means around USD 810 million (SIPA, 2022). Cacao production of Ecuador's Amazon region is concentrated in small and medium-size farmers (owning <5 ha). Most of farmers grow the crop under a traditional agroforestry system known as "chakra", in contrast with other regions where the prevailing management system is monoculture and the cacao variety cultivated is the one known as "Colección Castro Naranjal" (CCN51). The chakra is a diversified system where the owning family produces a great variety of food, including cacao (mostly the Fino de Aroma autochthonous variety) and other products (wood, fiber, etc.) for self-consumption and local sale (Vera et al., 2019; Heredia et al., 2021). This agroforestry system also provides a large number of ecosystem benefits (climate maintenance, carbon sinks, nutrient cycles, biodiversity reservoirs, etc.), which are key to environmental sustainability (Jadan et al., 2012; Vera et al., 2019; Niether et al., 2020; Lori et al., 2022). This aspect is important for the Amazon region, which is one of the world's biodiversity hotspots, which currently suffers of growing pressure on natural resources due to the expansion of the agricultural frontier, the spread of monoculture, and the excessive use of synthetic chemical fertilizers and pesticides (Foley et al., 2011; Vasco et al., 2021).

From a production perspective, cacao grown in agroforestry systems such as conventional (CA) or organic (OA), requires low-intensity management in terms of external inputs (fertilizers, energy, etc.). Family labor is predominant and the yields tends to be low or very low, which also causes low economic profitability (Subía et al., 2014; Paredes et al., 2019; Huera-Lucero et al., 2020). Previous studies on the cacao production of Ecuador's Amazon region have focused on topics such as generation and transfer of agroforestry technology (Virginio et al., 2014), conservation, use of agrobiodiversity and genetic improvement (INIAP, 2021), and integrated pest management (Nieto and Caicedo, 2012; Suh and Melua, 2022). Despite the importance of this crop, no studies about its environmental impact and economic viability have been carried out to visualize the differences between agroforestry management systems (conventional vs. organic). In order to fill this gap, this study used the life cycle analysis (LCA) methodology, which is an internationally tool that allows to assess the environmental impact of a good or service according to different impact categories (use of energy, global warming potential, eutrophication, etc.) and functional units (ISO, 2006). LCA makes it possible to generate scientific and rigorous information enabling the identification of the main hotspots of one or several processes and/or to develop models (Nabavi-Pelesaraei et al., 2017; Ghasemi-Mobtaker et al., 2022) to guide production and political decision-making (Notarnicola et al., 2017; Sonnemann et al., 2018; Nabavi-Pelesaraei et al., 2022a).

LCA methodology has been widely used to evaluate the climate or exegetic impact of food (Clune et al., 2017; Mostashari-Rada et al., 2020; Nabavi-Pelesaraei et al., 2022b), to highlight the environmental benefits of organic production (Smith et al., 2015; Meier et al., 2015) or assessing the use of production technologies, policies or strategies (Pérez-Neira et al., 2021). In the case of subtropical crops, there are some studies focused on analyzing the carbon footprint of exported bananas (Iriarte et al., 2014; Coltro and Karaski, 2019), or the extent to which the organic management of coffee cultivated (Muner et al., 2015; Basavalingaiah et al., 2022) reduces the crop's impact in various categories. With regard to cacao, most works have focused on analyzing the full life cycle of chocolate using different impact categories (GHG emissions, energy, eutrophication, etc.) (Miah et al., 2018; Bianchi et al., 2021; Boakye-Yiadom et al., 2021). Those studies have shown that the production of raw materials, particularly cacao, and the manufacturing of chocolate are the stages of the process that have a major impact (Pérez-Neira, 2016a; Recanati et al., 2018). Examining the differences in the management of cacao farms, Steiger (2010) proved that organic chocolate, in contrast with conventional chocolate, can reduce the carbon footprint; whereas Pérez-Neira et al. (2020b) highlighted the role of transportation in maintaining or cancelling the environmental benefits obtained in the production phase.

Another studies have analyzed the environmental impact associated with the on-farm phase of the production process (Table 1). Some studies have highlighted the differences between agroforestry systems and monocultures (Utomo et al., 2016; Parra-Paitan and Verburg, 2022), while others have contributed to the debate by examining the differences between organic and conventional management (Akrofi-Atitianti et al., 2018; Pérez-Neira et al., 2020a; Armengot et al., 2021). In general terms, agroforestry systems (particularly, the organic ones) obtain better environmental results than conventional monocultures, mainly due to the latter use synthetic chemical fertilizers and pesticides (Pérez-Neira et al., 2020a; Armengot et al., 2021). In the case of Ecuador, Pérez-Neira (2016b) evaluated the energy efficiency of producing cacao under CA and OA systems in the coastal province of Guayas. Organic systems are more efficient in the use of non-renewable energy, although the statistical significance of this difference is limited. Even though most of these studies do not evaluate the economic viability of cacao farms, the trade-offs between economic and environmental results cannot be ignored when decisions concerning sustainability are taken (Pérez-Neira, 2016b; Akrofi-Atitianti et al., 2018). Consequently, economic profitability is an important factor of change and one of the strong spots of conventional systems in the short term, particularly of monocultures (Seufert et al., 2012; Armengot et al., 2016). However, organic and/or agroecological agriculture has a great economic potential that needs to be developed (Van der Ploeg et al., 2019).

As seen in Table 1, the literature has not yet delved into the analysis of agronomical management systems, particularly in their economic viability. In addition, to the best of our knowledge, no previous studies have been published about the environmental and economic behavior of cacao production in the Ecuadorian Amazon region. Consequently, the main objective of this work was twofold: 1) to evaluate the environmental impact (using the LCA methodology and several indicators of environmental and economic efficiency at farm level); and 2) to assess the economic viability of the production management of cacao agroforestry systems in Ecuador's Amazon region (calculating the profitability of the crop based on the sale of cacao and other co-products). Two types of agroforestry system management: conventional vs. organic were compared. For this purpose, primary information was gathered from 90 farms distributed into six cacao producers' associations operating in three Amazon provinces (see the methodology section). This research discusses the main hotspots of the crop, as well as provides certain technical, production and policy recommendations aimed to improve sustainability in the afore-mentioned context.

## 2. Materials and methods

### 2.1. Case study: sample selection, boundaries, functional unit and inventory

This study was carried out in three provinces in the central-northern area of Ecuador's Amazon region: Napo, Orellana and Sucumbíos. The annual

**Table 1**
Main works on the environmental and economic impact of cacao/chocolate using a LCA methodology.

| Sphere of evaluation | Country (cacao) to country (chocolate) | Boundaries | Evaluation | | Organic | Reference |
|---|---|---|---|---|---|---|
| | | | *Main environmental impacts* | *Economic impact* | | |
| **Supply chain** | | | | | | |
| Cacao production and processing | Ghana | Cradle to grave | AD, AP, EP, FAETP, GW, HT, OD, POCP, TETP. | No | No | Ntiamoah and Afrane (2008) |
| Organic and conventional chocolate production | Ghana to Switzerland | Cradle to retailer | GWP. | No | Si | Steiger (2010) |
| Aluminum- and paper-wrapped chocolate | Germany to Europe | Cradle to grave | GWP | No | No | Jungbluth and Konig (2014) |
| Chocolate manufacture | Different countries to Italy | Cradle to process | CED, GWP, OD, TE, WE. | No | No | Vesce et al. (2016) |
| Environmental impact of dark chocolate | Ecuador to different countries | Cradle to retailer | CED, GWP. | No | No | Pérez-Neira (2016a) |
| Cacao production and processing | The Philippines | Cradle to process | AC, GWP, HT, TE. | No | No | Leyte et al. (2017) |
| Dark chocolate in Italy | Peru to Italy | Cradle to grave | AC, AD, CED, EU, GWP, OD, PO. | No | No | Recanati et al. (2018) |
| Confectionery products | The Philippines to the United Kingdom | Cradle to grave | AD, ALO, GWP, TE, ULO, WF | No | No | Miah et al. (2018) |
| Production and consumption of chocolate products | United Kingdom | Cradle to grave | ALO, FE, FWE, CED, GWP, HT, ME, MD MET, NLT, OD, POF, TA, TE, ULO. | No | No | Konstantas et al. (2018) |
| When transportation cancels the ecological benefits of production | Ecuador to different countries | Cradle to retailer | AC, AD, CED, EU, FWE, GWP, HT, OD, PO, TE. | No | Si | Pérez-Neira et al. (2020b) |
| Different chocolates | Ghana to different countries | Cradle to retailer | AC, AD, CED, EU, FWE, GWP, HT, ME, OD, PO, TE. | No | No | Boakye-Yiadom et al. (2021) |
| Different chocolates | Ecuador, Ghana, Indonesia to Italy | Cradle to grave | AC, AD, CED, EU, GWP. | No | No | Bianchi et al. (2021) |
| **On-farm phase** | | | | | | |
| Carbon footprint of conventional agroforestry systems | Colombia | Cradle to farm gate | GWP. | No | No | Ortiz et al. (2016) |
| Agroforestry systems and monocultures | Indonesia | Cradle to farm gate | AC, EU, GWP. | No | No | Utomo et al. (2016) |
| Different production management systems | Ecuador | Cradle to farm gate | CED, EROI. | Si | Si | Pérez-Neira (2016b) |
| Climate-intelligent agriculture | Ghana | Cradle to farm gate | GWP. | Si | Si | Akrofi-Atitianti et al. (2018) |
| Different production management systems | Bolivia | Cradle to farm gate | CED. | No | Si | Pérez-Neira et al. (2020a) |
| Food-energy-water nexus according to different management systems | Bolivia | Cradle to farm gate | AC, AD, CED, EU, FWE, GWP, HT, LF, MAE, OD, PO, TE, WF | No | No | Armengot et al. (2021) |
| Agroforestry systems vs. monocultures at farm level | Ghana | Cradle to farm gate | AC, DALY, FWE, GWP, HT | No | No | Parra-Paitan and Verburg (2022) |
| Different agroforestry systems | Ecuadorian Amazon region | Cradle to farm gate | AC, AD, CED, FWE, GWP, HT, LF, OD; PO, TE, WF. | Si | Si | This study |

AC = Acidification; AD = Abiotic depletion; ALO = Agricultural land occupation; CED = Cumulative energy demand; DALY = Disability-adjusted life years; EU = Eutrophication; EP = Eutrophication potential; EROI = Energy return on investment; FAETP = Freshwater aquatic ecotoxicity potential; FE = Freshwater eutrophication; FWE = Freshwater ecotoxicity; GWP = Global warming potential; HT = Human toxicity; LF = Land footprint; MD = Mineral depletion; MET = Marine ecotoxicity; NLT = Natural land transformation; OD = Ozone layer depletion; PDF = Potentially disappeared fraction of species; PO = Photochemical oxidation; POF = Photochemical oxidant formation; POCP = Photochemical ozone creation potential; TA = Terrestrial acidification; TE = Terrestrial ecotoxicity; TETP = Terrestrial ecotoxicity potential; ME = Marine eutrophication; ULO = Urban land occupation; WE = Water ecotoxicity; WF = Water footprint.

precipitation in those provinces fluctuates between 3400 and 3900 mm, the average temperature between 22 °C and 24 °C, and the altitude between 250 and 600 m a.s.l. (Climate-Data.org, 2022). Cacao agroforestry in the Amazon is characterized by very diverse agroecosystems and integrated management where there are also different timber trees (laurel, cedar, etc.), fruit trees (guaba, orange, chontaduro, among others), short cycle crops (banana, cassava, manioc, corn), medicinal plants (guayusa) and small animals such as chickens, hens, etc. In general terms, the planting density for cocoa is 4 m × 4 m. The environmental and economic analysis was based on empirical data gathered from 90 cacao farms, 44 of which were managed under a conventional agroforestry system and 46 under an organic agroforestry system (50 % of them were in the process of obtaining the organic certification).

The sample was designed in accordance with technical and production criteria. Farmers who carried out a crop management of agroforestry systems (pruning, plague control, fertilization, etc.) and produced a minimum yield (≥ 200 kg/ha) were selected. Farms were selected with help from the field technicians of the Estación Experimental Central de la Amazonía (Central Experimental Station of the Amazon region), which is managed by the Instituto Nacional de Investigaciones Agropecuarias (INIAP, National Agricultural and Livestock Farming Research Institute), as well as from agricultural extension officers of the Ministry of Agriculture and Livestock Farming of Ecuador and the cacao producers' associations in the region. Those farms that managed crops poorly or that only harvested cacao (without any management) were excluded (both situations are very common in the studied area). The selected farms allow to quantify and compare the environmental impact and economic performance of production systems with minimal management (fertilization, pruning, crop protection, etc.). Quantitative data, which are referred to 2020, were collected using face-to-face questionnaires conducted between March 2020 and March 2021. Most of the interviewed farmers (especially CA) do not have production records. Therefore, to improve its quality, the information obtained was contrasted with the one available from cooperatives and/or other primary sources (technicians, INIAP reports, etc.). For example, the sold production and/or the purchase of inputs were checked against the records of the cooperative. As regards to certified OA, farmers keep records to comply with the obligations of the certifying companies.

The boundaries of the system were determined from a cradle to farm gate approach. In order to perform the environmental and economic analysis, three functional units were selected: a) 1 kg of cacao; b) 1 kg of output sold, which, in addition to cacao, included other co-products (yuca, banana, etc.); and c) 1 ha (this unit was mostly used for economic analysis). Based on the data gathered through the questionnaires, an inventory was created that included physical and economic information on the main inputs used, as well as on the yield of cacao and other products sold (mainly banana and yuca). No information was collected on production for self-consumption. The inputs were divided into five large groups according to their function: i) fertilization: amount of fertilizers used, whether organic (manure, compost, etc.) or inorganic (10–30-10 NPK, muriate of potash, etc.); ii) crop protection: amount of herbicides, pesticides and fungicides applied (glyphosate, cuprous hydroxide, etc.); iii) petroleum derivatives: amount of fuel and oil consumed, mostly for the use of weeding machines and, exceptionally, motorized or gas pumps to dry cacao beans. When this information was not available, consumption was estimated based on available technical data (machinery, hourly consumption, etc.); iv) tools and machinery: inventory of the tools and machines used to manage the crop (weeding machines, pruning material, sprayers, gloves, etc.), the useful life of each tool was estimated according to Armengot et al. (2021); v) human labor: only paid-labor has been considered for the economic analysis. Although unpaid family work is the most abundant, it has not been considered because it does not represent a cost to the farms (see section 2.2.2).

### 2.2. Analysis of the environmental and economic impact of cacao production

#### 2.2.1. Environmental dimension

From the primary information and following the methodological recommendations found in ISO (2006) and Guinee (2002), twelve impact categories were estimated: land footprint (LF); non-renewable cumulative energy demand (CED); global warming potential (GWP 100y); water footprint (WF); abiotic depletion (AD); ozone layer depletion (OD); human toxicity (HT); terrestrial ecotoxicity (TE); photochemical oxidation (PO); acidification (AC); eutrophication (EU) and freshwater ecotoxicity (FWE). With the exception of LF, which was estimated using Eq. (A1), the rest of the impact categories were calculated from Eq. (A2) (both included in the Appendices). The calculations were made using the CML-IA baseline LCIA methodology, the Ecoinvent 3.5 and agribalyse 3.0 databases and the SimaPro software version 9.1.08. In the particular case of WF, the AWARE 1.04 methodology was used. The agroforestry systems analyzed were rain-fed and, for this reason, irrigation was not included in the analysis of the WF.

#### 2.2.2. Economic dimension

To tackle the economic dimension, a cost-profit analysis was carried out. The income derived from the sale of cacao and other co-products (yuca, banana, etc.) was estimated and the total cost (TC) for each farm was calculated as the sum of the costs of the used inputs (Ghasemi-Mobtaker et al., 2022). The following costs were included: fertilizers, crop protection, petroleum derivatives, labor (paid) and the amortization of the of tools and machinery. The net margin (the difference between total income and total cost) (Eq. (A6)) was used as a way to approach the economic viability of the crop. This indicator provides serves as a proxy of the net disposable income per hectare generated by agroforestry systems and received by households.

#### 2.2.3. Environmental and economic efficiency indicators

Additionally, five environmental and economic efficiency indicators were estimated: (i) non-renewable energy return on investment (EROI) (Eq. (A3)) and (ii) energy return on water investment (EROWI) (Eq. (A4)), which measure the efficiency in the use of non-renewable energy and water to produce one unit of energy output (Armengot et al., 2021); (iii) economic return on investment (EcoROI), which approaches the efficiency in generating income in relation to the expenditure (Eq. (A5)); (iv) energy intensity (EI), which measures the output of food (kg) and the value added (USD) generated according to the use of non-renewable energy (Eq. (A7)); and (v) GHG emission intensity (GHG I), which quantifies the GHG emissions per unit of net margin (Eq. (A8)) (all equations are shown in the Supplementary Materials).

### 2.3. Statistical analysis: contrast between conventional and organic management

Shapiro and Wilk (1965) test was carried out to determine the normality of all the variables. Given the high positive skewness and the presence of outliers (Fig. A1), none of the variables analyzed can be considered normal. Consequently, in order to compare their distribution, the non-parametric Mann and Whitney (1947) test for two independent samples (CA and OA) was performed. Moreover, the estimated difference of the location parameters between conventional and organic farms and their corresponding nonparametric 95 % confidence intervals (Hollander and Wolfe, 1973) was also computed. All analyses and plots were performed using R statistical software (v4.1.2; R Core Team, 2021) and the 'tidyverse' package (v1.3.0; Wickham et al., 2019).

## 3. Results

### 3.1. Food production, energy, GWP, WF, and economic and environmental efficiency in the production of organic and conventional cacao

As observed in Table 2, the LF of the OA systems was larger than that of the CA systems, requiring 2.78 ha (on average) to produce 1 ton of cacao in contrast to the 2.22 ha needed in conventional farms. CA systems demand approximately nine times more energy (CED) and produce also around nine times more GHG emissions

**Table 2**
Food production, energy, GHG emissions, WF, and economic efficiency in the production and sale of cacao grown in agroforestry systems (conventional vs. organic): a) cacao and b) output sold (cacao + other products). The table also shows the 95 % trimmed means for all the variables in both samples (CA and OA) in order to eliminate the influence of outliers or data points on the tails that may unfairly affect the traditional mean.

| Particulars | Unit | CA | OA | CA vs. OA | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 95 % trimmed means | | < or > | *p*-value | Estimated difference | 95 % CI | |
| A. Cacao | | | | | | | | |
| Food production | | | | | | | | |
| Land footprint | ha/t | 2.22 | 2.78 | < | 0.00 | 0.01 | 38.9 | 6.2 |
| Energy and GHG emissions | | | | | | | | |
| CED | MJ/kg | 3.27 | 0.36 | > | 0.00 | 2.60 | 1.80 | 3.4 |
| GWP | kg $CO_2$ – eq/kg | 0.300 | 0.034 | > | 0.00 | 0.25 | 0.18 | 0.3 |
| Water | | | | | | | | |
| WF | m3/kg | 0.305 | 0.009 | > | 0.00 | 0.28 | 0.20 | 0.37 |
| Economic efficiency | | | | | | | | |
| Income | USD/ha | 825.0 | 735.0 | > | 0.03 | 132.86 | 4.70 | 258.0 |
| TC | USD/ha | 173.9 | 89.8 | > | 0.00 | 86.79 | 49.0 | 118.5 |
| Net margin | USD/ha | 665.6 | 607.7 | – | 0.34 | 62.45 | −72.7 | 198.3 |
| Efficiency indicators | | | | | | | | |
| EROI | – | 5.95 | 53.50 | < | 0.00 | −45.47 | −60.6 | −30.3 |
| EROWI | MJ cacao/$m^3$ | 63.83 | 2069.5 | < | 0.00 | −1557.3 | −2120 | −1177 |
| EcoROI | – | 5.69 | 7.51 | < | 0.01 | −2.96 | −8.45 | −0.57 |
| EI | Kg/MJ | 0.31 | 2.75 | < | 0.00 | −2.34 | −3.12 | −1.56 |
| | USD/ MJ | 0.48 | 3.93 | < | 0.00 | −3.34 | −4.84 | −1.66 |
| GHG I | kg $CO_2$ – eq/$ | 0.170 | 0.023 | > | 0.00 | 0.15 | 0.11 | 0.21 |
| B. Output sold (cacao + other crops) | | | | | | | | |
| Economic efficiency | | | | | | | | |
| Income | USD/ha | 867.5 | 744.4 | > | 0.00 | 184.90 | 51.9 | 327.5 |
| Net margin | USD/ha | 721.00 | 639.37 | – | 0.11 | 103.20 | −27.59 | 252.3 |
| Efficiency indicators | | | | | | | | |
| EROI | – | 6.17 | 53.67 | < | 0.00 | −45.71 | −74.7 | −32.97 |
| EROWI (i) | MJ/$m^3$ | 74,71 | 2085,66 | < | 0.00 | −1576.9 | −2139 | −1213 |
| EcoROI | – | 6.19 | 7.61 | < | 0.02 | −2.82 | −8.16 | −0.46 |
| Energy intensity | Kg/MJ | 0.51 | 3.21 | < | 0.00 | −2.54 | −4.06 | −1.73 |
| | USD/MJ | 0.50 | 4.00 | < | 0.00 | −3.50 | −5.80 | −1.97 |
| Carbon intensity | kg $CO_2$ – eq/USD | 0.168 | 0.022 | > | 0.00 | 0.14 | 0.09 | 0.18 |

(GWP) per kilogram of cacao than OA systems. The WF associated with the inputs used in conventional management was also larger: 0.305 vs. 0.009 $m^3$/kg. In economic terms, the higher prices paid for organic cacao (+11.4 %) did not compensate the farms' low performance, and organic incomes were 10 % lower. Nevertheless, since TC is higher in CA, there are no statistically significant differences between the net margin of the two managements. Fertilization and crop protection were the inputs that carried the most weight (%) in CA systems,

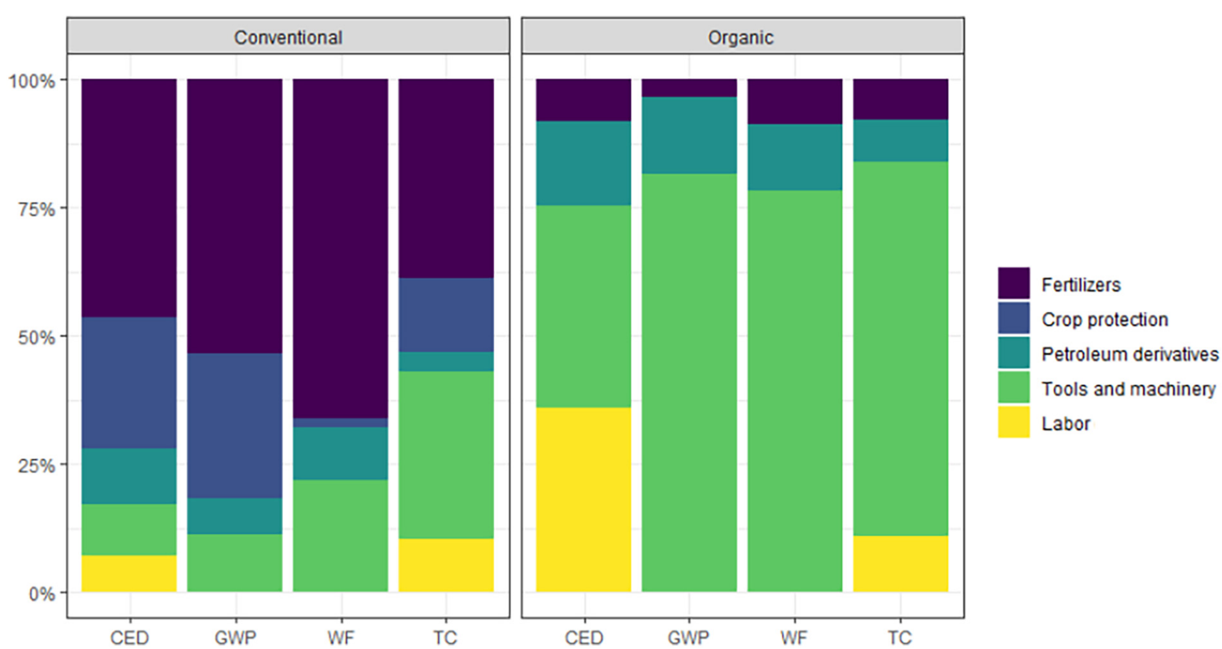


**Fig. 1.** Structure of the environmental impacts (CED, GWP and WF) and economic costs (TC) by production management in % (CA vs. OA).

particularly in relation to the categories of GWP and CED (Fig. 1). In monetary terms, the purchase of tools and machinery was important, while the cost of labor was relatively low, considering that it was mostly provided by the owning family members, and therefore, it was not remunerated. In the case of OA systems, the use and purchase of tools and machinery represents the largest input (%) in all the analyzed categories.

When the efficiency of the systems was analyzed in terms of energy, emissions and added value, OA systems showed better results for all indicators; for instance, the estimated difference between CA and OA is −45.71 (EROI) and − 2.82 (EcoROI). On the other hand, organic production is associated with higher energy intensity, meaning that it is capable of producing more kilograms of cacao and added value per unit of energy used than conventional systems. These results vary slightly when the output sold (cacao + other crops) is taken into consideration. In this sense, the data indicated that conventional farms sold more co-products, which allowed to improve their net margin per hectare by 8 %, in contrast to only 5 % in organic farms, though the difference between the net margin of the two managements is still statistically non-significant. OA systems continue to achieve better results in relation to energy use, energy efficiency, GHG emissions and water use (Table A1), especially considering that none of the economic calculations included the monetary value of all the food and other products destined to self-consumption, which is higher in the organic agroforestry systems.

### *3.2. Additional environmental impact categories: LCA approach*

Regardless of the functional unit selected, the analysis of the rest of the impact categories shows that CA systems have larger environmental impacts than organic ones (Table 3 and Table A2). For instance, the AC of the CA systems per kilogram of cacao was fifteen times higher than that of the OA systems; while their FWE was six times higher, and the EU was twelve times higher. Differences between systems were mostly determined by the use of chemical fertilizers and crop protection inputs (herbicides, pesticides, etc.) in conventional farms (Fig. A2).

## 4. Discussion

### *4.1. Environmental and economic behavior of the cacao production of Ecuador's Amazon region*

The crop yield of the analyzed farms (both OA or CA systems) are higher than the average recorded for the Amazon region (250–440 kg/ha) (ESPAC, 2022), but they are still below the Ecuadorian average (621 kg/ha) (Faostat, 2022). Armengot et al. (2016) report similar cacao yields in CA and OA while Pérez-Neira (2016b) and Akrofi-Atitianti et al. (2018) finds higher yields in OA connecting this fact to good agroecological practices. In environmental terms, it is widely acknowledged that organic agriculture allows to reduce oil dependence, improves efficiency and reduces considerably the various impacts per unit of area, although these results are less conclusive per kilogram of product due to the differences in yields (Seufert et al., 2012; Meier et al., 2015; Smith et al., 2015). However, in the case of the Ecuadorian Amazon region, the gap between the yield in favor of CA systems does not compensate the environmental impact derived from the use of synthetic chemical fertilizers and pesticides. Armengot et al. (2021) and Pérez-Neira et al. (2020b) obtained similar results, although the latter do not find any significant differences in GWP, CED, OD and AC for Ecuadorian cacao. The data showed how the impacts of Amazon agroforestry systems are lower than those calculated in other studies for other areas (Recanati et al., 2018; Pérez-Neira et al., 2020b), and highlighted the low intensity of the use of external inputs in agroforestry systems (even conventional ones). In relation to other subtropical crops, Roibás et al. (2014) and Muner et al. (2015) also underline the importance of implementing organic management practices in order to reduce the GHG emissions and improving the energy efficiency of banana and coffee productions, respectively.

As pointed out before, most previous studies on cacao have focused on analyzing the life cycle of chocolate (Pérez-Neira, 2016a; Recanati et al., 2018; Miah et al., 2018; Bianchi et al., 2021; Boakye-Yiadom et al., 2021; Parra-Paitan and Verburg, 2022) and/or comparing management systems (Pérez-Neira, 2016b; Utomo et al., 2016; Bianchi et al., 2021), while the economic viability of the crop is the least researched aspect (Table 1). The data presented in this study show how conventional cacao in the Amazon region produces higher income, but it is not more profitable than organic cacao (no statistically significant difference). In both systems, the labor in the chakra is mostly performed by families and only rarely external labor is hired. The farming families work for the conservation of the integrated agrobiodiverse chakras to ensure food safety, preserving forest species, fruit trees, functional and medicinal plants, and providing ecosystem functions (biodiversity, carbon sequestration, etc.) (Vera et al., 2019 and 2021; Paredes et al., 2019; Niether et al., 2020; Lori et al., 2022). Despite this, the higher prices paid for organic products (+11 %) are not enough to generate a clear economic incentive for adopting organic management. In fact, the low economic profitability of the crop (in terms of production costs and low market prices) may become an incentive to abandon sustainable management systems in favor of more profitable ones, particularly monocultures (Subía et al., 2014; Huera-Lucero et al., 2020; Heredia et al., 2021; Vasco et al., 2021). The pressure on families who implement a biodiverse management system in their chakras caused by the expansion of monoculture is, therefore, a serious threat to the protection and conservation of the territory, to food safety and to biodiversity, and involves an increase in other environmental impacts that cannot be ignored by public authorities (LOASFAS, 2017).

**Table 3**
LCA impact categories per kilogram of cacao in agroforestry systems (CA vs. OA). The table also shows an estimate of the differences of the location parameters between conventional and organic farms and the corresponding nonparametric 95 % confidence intervals (95 % CI).

| Particulars | Unit | CA | OA | CA vs. OA | | | | |
|---|---|---|---|---|---|---|---|---|
| | per kg cacao | 95 % trimmed means | | < or > | p-value | Estimate | 95 % CI | |
| AD | kg Sb eq | 1.43E-05 | 9.65E-07 | > | 0.00 | 1.30E-05 | 9.31E-06 | 1.53E-05 |
| OD | kg CFC-11 eq | 3.13E-08 | 5.06E-09 | > | 0.00 | 2.22E-08 | 1.76E-08 | 2.98E-08 |
| HT | kg 1.4-dB eq | 1.04E-01 | 3.46E-02 | > | 0.00 | 5.74E-02 | 3.71E-02 | 7.85E-02 |
| TE | kg 1.4-dB eq | 8.47E-03 | 1.18E-04 | > | 0.00 | 7.88E-03 | 3.84E-03 | 1.06E-02 |
| PO | kg $C_2H_4$ eq | 1.05E-04 | 1.26E-05 | > | 0.00 | 5.21E-05 | 4.66E-05 | 1.44E-04 |
| AC | kg $SO_2$ eq | 1.82E-03 | 1.70E-04 | > | 0.00 | 1.54E-03 | 1.10E-03 | 1.89E-03 |
| EU | kg $PO_4$ eq | 9.59E-04 | 7.69E-05 | > | 0.00 | 8.63E-04 | 4.56E-04 | 1.03E-03 |
| FWE | kg 1.4-dB eq | 9.57E-02 | 1.50E-02 | > | 0.00 | 7.11E-02 | 4.03E-02 | 8.80E-02 |

### *4.2. Hotspots and proposals for the improvement of organic production*

The low profitability was one of the main hotspots identified in the Ecuadorian Amazon agroforestry systems, particularly in the OA. This is the result of their yields, which are much lower than those of conventional systems (particularly in relation to monocultures), and the lack of better prices for their products. Prior studies have shown how the improvement of organic management may lead to an increase in productivity and consequently to a better economic performance (Akrofi-Atitianti et al., 2018). In the Ecuadorian coast, Pérez-Neira (2016b) estimated that the profitability was three times higher in OA systems than in CA systems (1500 vs. 500 USD/ha), but lower than that obtained for monocultures (2300 USD/ha). Comparing to the results of this study, the profitability of conventional monocultures in the coast is three times than that obtained in agroforestry systems of the Amazon region (even if the production management of those systems is good compared with the reality of the area under study). On the other hand, it should be noted that the intensification of organic production in the coast, mainly through irrigation, has an environmental cost; energy efficiency decreases due to the higher use of fossil fuels to pump the water (Pérez-Neira, 2016b). Beyond productivity and given that agroforestry systems are capable of producing more food per hectare than monocultures, a good management of the co-products could contribute to improve the income of farms substantially and increase their profitability up to the level of monocultures (Armengot et al., 2016). In this sense, the role of cooperatives and public policies are essential to support and guide farming families, not only in accessing high-value markets, as well as in improving their participation in local markets and in developing other strategies (processing, quality seals, price differences, etc.) (Donovan et al., 2017; Jacobi et al., 2015; Van der Ploeg et al., 2019), which may allow to valorize, from a monetary point of view, the agrobiodiverse production of the Amazon chakra.

Although the management of the selected farms can be described as average or good compared to others in the area, there still is not much room for improvement. Thus, the yield of OA systems could substantially increase by implementing an integrated agroecological plan or improving the existing one (Huera-Lucero et al., 2020; Suh et al., 2022). Among the measures suggested are the integrated management of pests and diseases; organic soil management (for instance, soil liming to control acidity); organic fertilization with bioles, compost or a vegetation cover composed of leguminous plants; the implementation of formative and sanitary pruning; or the use of biological controllers and cupper-based fungicides (INIAP, 2020). The environmental and economic impact of implementing these agroecological measures is not still estimated and will show the hotspots, strengths and scope of these measures. Finally, another fundamental challenge that cacao production is facing in Ecuador's Amazon region is the lack of scientific advances in agroecological research and the adoption of new practices as part of the farmers' daily work. This challenge entails an improvement of rural expansion services and public policies, as reflected in the current Ecuadorian regulation (Reglamento LOASFAS, 2020).

### *4.3. Limitations of the study and future directions*

The current article has some limitations such as: a) the selected sample was based on a specific profile of cacao producer (with an average or good management), and it should be expanded to include other production profiles; b) some aspects related to GHG emissions associated with harvest waste should also be considered (Tinoco et al., 2020; INIAP, 2020); c) the LCA should also be expanded to evaluate the remaining phases of the production process until the consumption phase (Clune et al., 2017; Iriarte et al., 2014); d) LCA performance can be enhanced by means of different modeling techniques (Ghasemi-Mobtaker et al., 2022), new environmental impact indices (Khanali et al., 2022) or others indicators such as exergy (Mostashari-Rada et al., 2020; Nabavi-Pelesaraei et al., 2017 and 2022b) or other ecosystem services assessments (Liu et al., 2019) and e) the economic analysis should be improved by including, for instance, possible incomes obtained from the sale of the total output of co-products; by modeling profitability scenarios in a context of inflationary stress like the current one or including the role of self-consumption and unpaid family labor as key elements to understand the functioning of the peasant or indigenous economy in Ecuador (Van der Ploeg et al., 2019). In this sense, this work opens some interesting questions, such as why conventional farms sell more co-products, or what economic or institutional incentives organic farms would need to improve this aspect. These and other limitations open the door to further research.

## 5. Final remarks

This study analyzed the economic and environmental performance of the cacao production in agroforestry systems of Ecuador's Amazon region. The results showed how their yield per hectare is not high, especially when the production is organic. Nonetheless, OA systems had a lower environmental impact in all the analyzed categories (except for land footprint), they were more efficient in the use of energy and water, and even more economically efficient in terms of economic return on investment, energy intensity or GHG emission intensity. In addition, the analysis shows that economic profitability was the weakest point in both agroforestry systems. Low economic profitability may cause the abandonment of the sustainable management of agroforestry systems. In this sense, it is needed to concentrate research, agricultural extension and public policy efforts on supporting and rewarding the labor of small and medium-size farmers (which is currently poorly remunerated), who are struggling to keep afloat the economy and preserve the natural wealth of the Ecuadorian Amazon region.

## CRediT authorship contribution statement

**Carlos Caicedo-Vargas:** Conceptualisation, Investigation, Formal analysis, Methodology, Writing & results discussion; Resources.

**David Pérez-Neira:** Conceptualisation, Formal analysis, Methodology, Writing & results discussion.

**Julio Abad-González:** Formal analysis, Methodology, Visualisation, Writing & results discussion, Resources.

**David Gallar:** Conceptualisation, Writing & results discussion.

## Data availability

The authors do not have permission to share data.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A*A.1. Methodology*

*A.1.1. Environmental impact*

In order to estimate the Land Footprint, Eq. (A1) was used, whereas to calculate the impacts associated with the categories of non-renewable cumulative energy demand (CED), global warming potential (GWP 100y), water footprint (WF), abiotic depletion (AD), ozone layer depletion (OD), human toxicity (HT), terrestrial ecotoxicity (TE), photochemical oxidation (PO), acidification (AC), eutrophication (EU), and freshwater ecotoxicity (FWE), Eq. (A2) was employed.

$$LF = 1/Y \tag{A1}$$

In the above equation: LF = Land footprint; Y = Yield (t/ha).

$$EI_{(i)} = \sum I_{(j)} \text{ x } C_{(i,j)} \tag{A2}$$

In the above equation: $EI_{(i)}$ = Environmental impact *i* (where *i*: GWP; CED; AC, etc.) (unit/kg); $I_{(j)}$ = Input *j* (where *j*: fertilizers, energy, crop protection, machinery, tools, etc.) (unit/kg); $C_{(i,j)}$ = Characterization factor of impact *i* in relation to input *j*, which allows aggregating and homogenizing the releases (impact/ unit). As regards tools and machinery, the environmental impact of their production and maintenance was amortized over 1–5 years.

*A.1.2. Environmental and economic efficiency indicators*

Non-renewable energy return on investment (EROI), energy return on water investment (EROWI), and economic return on investment (EcoROI) were estimated from Eqs. (A3), (A4) and (A5), respectively. Net margin and ndicators energy intensity (EI) and GHG emission intensity (GHG I) were calculated using Eqs. (A5), (A6) and (A7).

$$EROI = EO/CED \tag{A3}$$

$$EROWI = (EO/Y)/WF \tag{A4}$$

$$EcoROI = I/TC \tag{A5}$$

In the above equations: EROI = Non-renewable energy return on investment; EO = Energy output (MJ/ha), which was calculated by multiplying the output (cacao and other crops) by the energy content of each foodstuff (MJ/kg) (Pérez-Neira et al., 2020a, 2020b); CED = Non-renewable cumulative energy demand (MJ/ha); EROWI = Energy return on water investment (MJ/$m^3$); Y = Yield (kg/ha); and WF = Water footprint of the inputs used in the management of the plots ($m^3$/ha); EcoROI = Economic return on investment; I = Income (USD/ha); TC = Total cost (USD/ha).

$$\text{Net Margin} = \sum \text{Income} - \sum TC \tag{A6}$$

$$EI = (Y \text{ or } AV)/CED \tag{A7}$$

$$GHG\ I = GWP/AV \tag{A8}$$

In the above equations: Net Margin ($/ha); Income = Income obtained by farmers from the sale of cocoa and other co-products (price for quantities sold); TC = Total Cost; The result of adding up all the monetary expenses of the farms (fertilization, labor -paid-, petroleum derivatives, etc.) plus the amortization of tools and machinery; EI = Energy intensity (kg/MJ or USD/MJ); Y = Yield (kg/ha); AV = Added value (USD/ha); CED = Non-renewable cumulative energy demand (MJ/ha); GHG I = Greenhouse gas emission intensity (kg $CO_2$-eq/USD); GWP = Global warming potential (kg $CO_2$-eq/ha).

*A.2. Results*

Table A1 shows the indicators related to food production, energy use, GHG emissions and water, while Table A2 synthesizes various LCA environmental impact categories. The data in both tables are in relation to 1 kg of output sold. Fig. A1 present the distribution of the main environmental impacts and economic indicators by production system and Fig. A2 presents the environmental impact structure according to different LCA categories.

**Table A1**

Food production, energy, GHG emissions and WF per kilogram of output sold (cacao + other crops) in conventional vs. organic agroforestry systems (CA vs OA). The table also shows the 95 % trimmed means for all the variables in both samples to eliminate the influence of outliers or data points on the tails that may unfairly affect the traditional mean.

| Particulars | Unit | CA | OA | CA vs. OA | | | | |
|---|---|---|---|---|---|---|---|---|
| Output sold | | 95 % trimmed means | | < or > | p-value | Estimated difference | 95 % CI | |
| Food production | | | | | | | | |
| LF | Ha/t | 1.31 | 2.22 | < | 0.00 | 0.01 | 14.29 | 2.69 |
| Energy and GHG emissions | | | | | | | | |
| CED | MJ/kg | 1.96 | 0.31 | > | 0.00 | 1.57 | 1.19 | 2.03 |
| GWP | kg $CO_{2-}$eq/kg | 0.18 | 0.03 | > | 0.00 | 0.14 | 0.10 | 0.19 |
| Water | | | | | | | | |
| WF | m3/kg | 0.17 | 0.01 | > | 0.00 | 0.16 | 0.08 | 0.22 |

**Table A2**
LCA impact categories per kilogram of output sold (cacao + other crops) in conventional vs. organic agroforestry systems (CA vs OA).

| Particulars | Unit per kg of output sold | CA | OA | CA vs. OA | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 95 % trimmed means | | < or > | p-value | Estimated difference | 95%CI | |
| AD | kg Sb eq | 7.79E-06 | 8.61E-07 | < | 0.00 | 6.84E-06 | 5.03E-06 | 9.89E-06 |
| OD | kg CFC-11 eq | 1.96E-08 | 4.20E-09 | < | 0.00 | 1.31E-08 | 9.02E-09 | 1.79E-08 |
| HT | kg 1.4-dB eq | 6.02E-02 | 3.04E-02 | < | 0.00 | 3.14E-02 | 1.75E-02 | 4.70E-02 |
| TE | kg 1.4-dB eq | 4.70E-03 | 8.26E-05 | < | 0.00 | 4.19E-03 | 2.17E-03 | 6.34E-03 |
| PO | kg $C_2H_4$ eq | 5.73E-05 | 9.83E-06 | < | 0.00 | 3.50E-05 | 4.36E-05 | 5.21E-05 |
| AC | kg $SO_2$ eq | 9.86E-04 | 1.37E-04 | < | 0.00 | 7.48E-04 | 5.12E-04 | 1.25E-03 |
| EU | kg $PO_4$ eq | 5.36E-04 | 5.48E-05 | < | 0.00 | 4.25E-04 | 2.45E-04 | 7.18E-04 |
| FWE | kg 1.4-dB eq | 4.90E-02 | 1.27E-02 | < | 0.00 | 3.42E-02 | 2.13E-02 | 5.27E-02 |

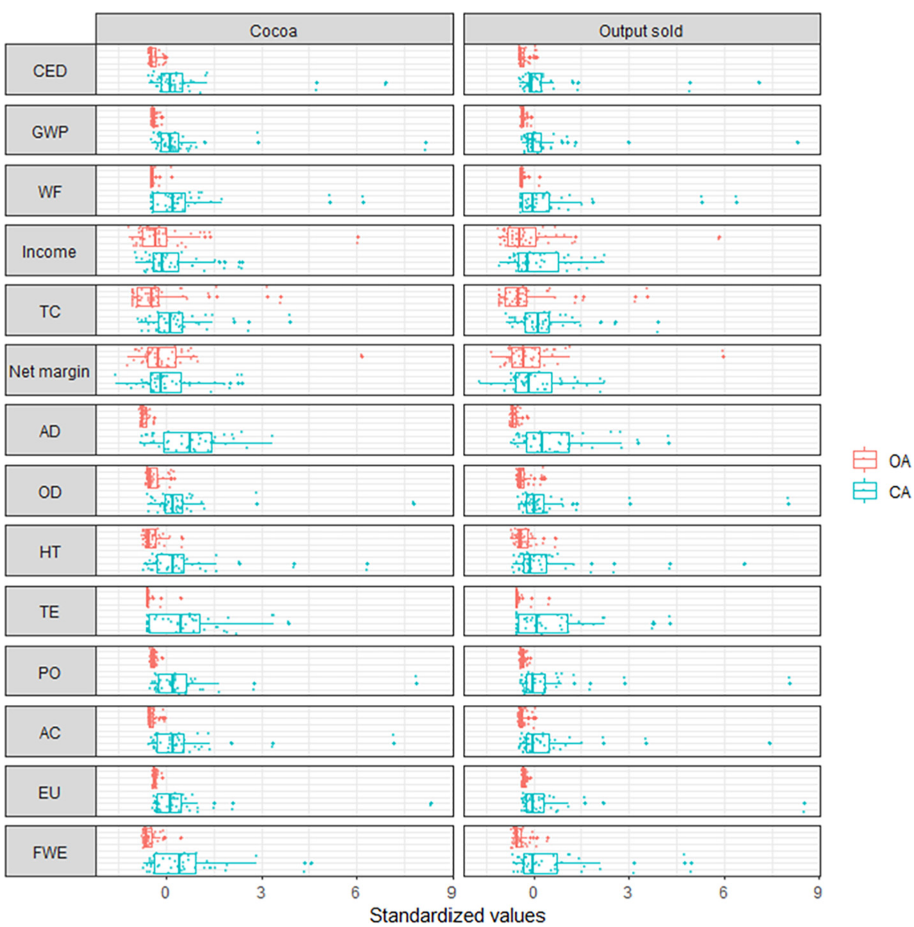


**Fig. A1.** Distribution of the main environmental impacts and economic indicators in conventional vs. organic agroforestry systems (CA vs OA): Cacao (impact per kg of cacao) and output sold (cacao + other crops) (impact per kg of output sold). Abbreviations: CED = Non-renewable cumulative energy demand; GWP = Global warming potential; WF = Water Footprint; TC = Total Cost; AD = Abiotic depletion; OD = Ozone layer depletion; HT = Human toxicity; TE = Terrestrial ecotoxicity; PO = Photochemical oxidation; AC = Acidification; EU = Eutrophication; FEW = Freshwater ecotoxicity.

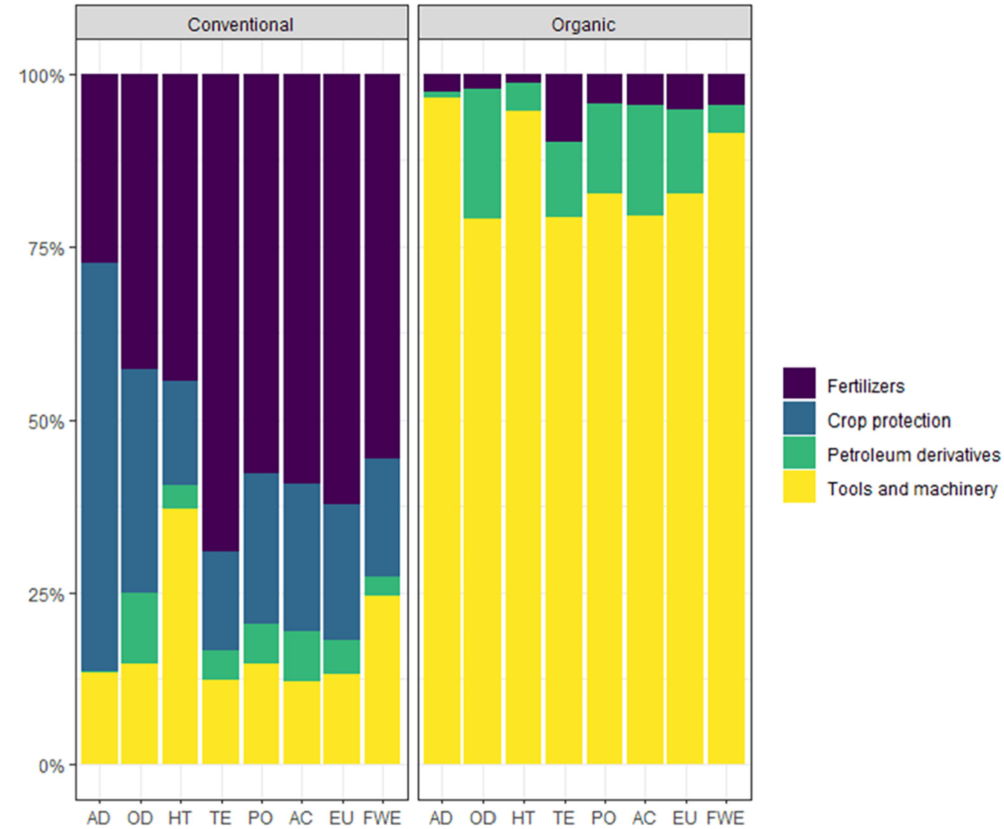


**Fig. A2.** Structure of LCA impact categories by production system. Abbreviations: AD = abiotic depletion; OD = ozone layer depletion; HT = human toxicity; TE = terrestrial ecotoxicity; PO = photochemical oxidation; AC = acidification; EU = eutrophication; FEW = freshwater ecotoxicity.

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