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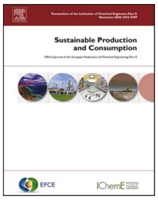

Agroecology as a means to improve energy metabolism and economic management in smallholder cocoa farmers in the Ecuadorian Amazon

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ABSTRACT

Cocoa is one of the most important crops in Ecuador, especially in the Ecuadorian Amazon, where >60,000 ha are dedicated to cocoa; 48,600 ha in production in 2021. Most of the cocoa area (82 %) is managed by smallholders with <10 ha under cultivation. Despite the socioeconomic and environmental importance of these systems, there are no previous studies that provide an integrated view of the energy metabolism and economic viability of different smallholder management styles. Consequently, the objective of this work is twofold: a) to estimate the aggregate energy and economic metabolism of small cocoa producers (< 10 ha) in the Ecuadorian Amazon and b) to investigate the existing differences in the technical-economic management styles of the crop. To this end, primary data were collected from a statistically representative sample of cocoa-growing areas distributed among 279 producers in 86 communities in the region, using the life cycle assessment (LCA) methodology and a cost-benefit analysis associated with management. Our data show that most smallholder farmers produce cocoa in low-input diversified agroforest system with a high share of unpaid family labor. At the Amazon level, smallholder farmers (< 10 ha) produced 16.9 million tons of food for the market with a non-renewable cumulative energy demand (NR CED) of 53.8 TJ (1343 MJ/ha), a carbon footprint (CF) of 8.16 Mt. CO_2-eq. (203.9 kg CO_2-eq/ha), and a net margin of 19.07 million $ (476.8 $/ha). On average, cocoa yields were estimated at 288 kg/ha, resulting in a NR CED and carbon footprint (CF) per kg of cocoa of 4.18 MJ and 0.98 kg CO_2-eq. Despite its apparent homogeneity, three distinct styles of crop management were identified by a cluster analysis. The results suggest that farms with good organic/agroecological management can have a similar income generating capacity to the more intensive conventional farms evaluated, but with better environmental outcomes. Consequently, the paper finally discusses the need to promote public actions and policies that allow for the scaling up and improvement of successful agroecological management in the Ecuadorian Amazon.

1. Introduction

The Ecuadorian Amazon is one of the most ecologically and culturally diverse regions in the world, where multiple forest landscapes, animal and plant species co-exist with the traditional cultures of indigenous peoples and/or nationalities that in turn maintain this biodiversity (Caballero et al., 2016; Paredes et al., 2019). However, in recent decades the Amazon is increasingly exposed to infrastructure expansion, pressure on natural resources and development projects, particularly, the expansion of the agricultural frontier with the advance of monoculture as a productive model that contributes to the destructuring of the territory and indigenous peoples (Foley et al., 2005; Richards et al., 2014; Vasco et al., 2021). Consequently, the evolution of land use in this region will be a determining factor for the future of the people who inhabit this culturally diverse territory and the ecological richness of its forests (Gray and Bilsborrew, 2020; Rivera et al., 2020; Huera-Lucero et al., 2020). This is particularly important in the case of cocoa production. Ecuador is the third largest exporter worldwide (7.9 % of the bean) (Faostat, 2022), occupying 12 % of the country's cultivated agricultural area (ESPAC, 2022). It is estimated that in the Amazon region there are 60,000 ha dedicated to cocoa (in 2021), of which 48,600 are in production, accounting for 6.5 % of Ecuador's cocoa (ESPAC, 2022), mainly in the provinces of Sucumbíos (47 %), Orellana (39 %)

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Acronyms

AC	Acidification
AFS	Agroforestry systems
CF	Carbon footprint
ECfw	Ecotoxicity, freshwater
EEco	Economic efficiency
EF	Environmental footprint
EI	Energy intensity
EO	Energy output
EUfw	Eutrophication, freshwater
EUm	Eutrophication, marine
EUt	Eutrophication, terrestrial
GHG	Greenhouse gas
HTc	Human toxicity, cancer
HTnc	Human toxicity, non-cancer
I CF	Carbon footprint intensity
In	Income
IR	Ionizing radiation
L EROI	Labor EROI
LCA	Life cycle assessment
LP	Labor productivity
LU	Land use
NM	Net margin
NR CED	Non-renewable cumulative energy demand
NR EROI	Non-renewable energy return of investment
OD	Ozone depletion
PM	Particulate matter
PO	Photochemical ozone formation
RU	Resource use, minerals and metals
TC	Total cost
WU	Water use

and Napo (12 %), where 98 % of cocoa production is concentrated (see Fig. 1). These provinces are also the most vulnerable territories due to the pressure of monoculture (particularly by international cocoa companies to meet growing consumer demand) which is causing major changes in land division, soil use and reduction of vegetation cover, and introducing the use of chemicals in agricultural production (Viteri and Toledo, 2020).

In the Amazon region, most of the cocoa area (approx. 82 %) is managed in small peasant and indigenous production units (< 10 ha) (ESPAC, 2022). According to official data, only 3 % of the total cultivated area is declared as “associated systems”, where cocoa is produced together with other crops (ibid.). However, this contrasts with the work of Torres et al. (2022), which highlights the importance of traditional agroforestry systems (AFS) locally called “Chakra” linked mostly to indigenous communities (Kichwa) that represent 48 % of agricultural producers in the Amazon (ESPAC, 2022). These AFS are characterized as systems with high productive and biological diversity among tree, plant and animal species linked to a common and environmentally friendly agricultural tradition (Virginio et al., 2014; Torres et al., 2014 and 2017). Thus, in addition to cocoa as the main cash crop (Subía et al., 2014), a wide variety of food (fruits, maize, cassava, small animals, etc.) and other non-edible goods (wood, medicinal herbs, etc.) are also produced in these systems (Vera et al., 2019 and 2020). Traditional management and the predominance of unpaid labor allows farming families higher effective income derived from cocoa (national and international markets) and other products (local markets) (Caicedo et al., 2022a; Heredia et al., 2021; Avadí et al., 2021). From an energetic metabolism approach, AFS usually present high efficiency and low dependence on the use of non-renewable energy (Muner et al., 2015; Armengot et al., 2021; Avadí, 2023), which allows the compatibility of productive uses and ecosystem functions - climate maintenance, carbon sinks, nutrient cycles, biodiversity reservoirs, etc. (Jadan et al., 2012; Lewandrowski et al., 2014; Vera et al., 2019; Niether et al., 2020; Purnomo et al., 2021).

In economic terms, AFS in the Ecuadorian Amazon have low productivity (Avadí et al., 2021; Caicedo et al., 2022b). Most cocoa is marketed through small intermediaries and/or smallholder associations (Avadí et al., 2021; Chakra Corporation, 2022). Despite the weak associativity in Ecuador, some associations play a key role in price

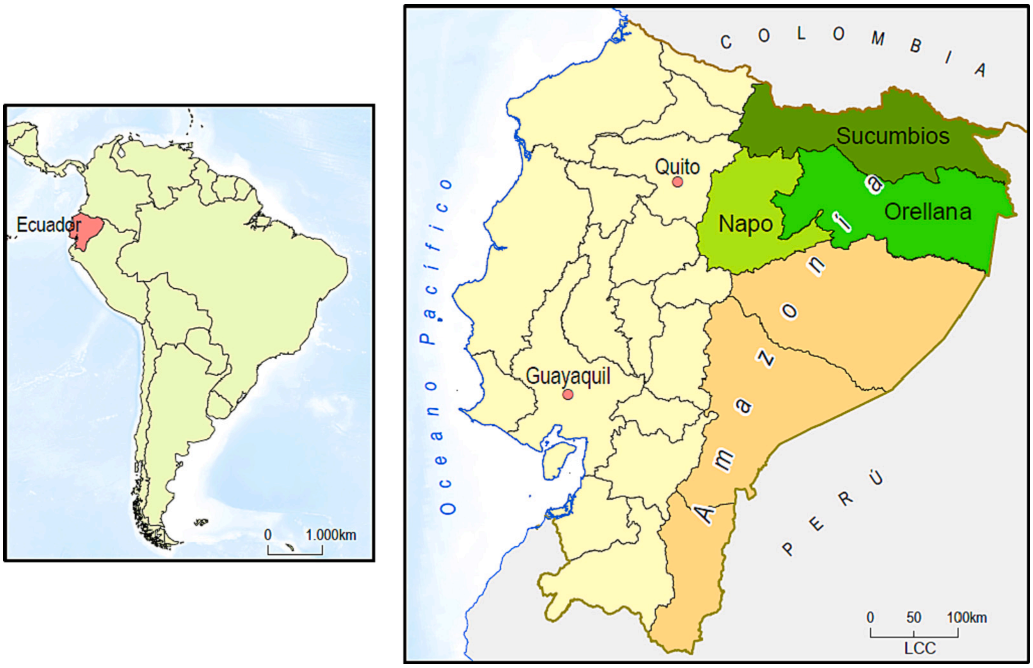

Fig. 1. Northern center of the Ecuadorian Amazon (Napo, Orellana and Sucumbíos).

negotiation, production advice and input collection (Torres et al., 2022). For example, they were pioneers in strengthening production in traditional systems, involving smallholder in decision making or introducing organic certified areas (INIAP, 2021). In this sense, and despite the apparent homogeneity in traditional systems, it is possible to affirm that there are different cocoa "management styles", i.e., distinctive ways of ordering and organizing the agricultural process that lead to different results in terms of productivity, markets, resource use, energy efficiency, etc. (van der Ploeg and Ventura, 2014; van der Ploeg et al., 2019). This is why organizations have been demanding agricultural education and training with an agroecological perspective that allows the development of the crop's economic potential under conservationist practices (Rosati et al., 2021; Paredes et al., 2022; Ntawuruhunga et al., 2023). There is, therefore, a growing need to promote an agroecological transition and upscaling where, in addition to the participation of farmer organizations (Mier et al., 2018; Futemma, 2021; Giraldo and Rosset, 2022), the development of strong public policies with an agroecological approach is urgent (González de Molina, 2013; MAG, 2018; FAO, 2018; Le Coq et al., 2020).

Previous work has focused on analyzing the economic performance and environmental impact of cocoa through life cycle assessment (LCA) methodology. For example, Utomo et al. (2016) or Parra-Paitan and Verburg (2022) analyze, among other impacts, greenhouse gas (GHG) emissions and energy use of AFS vs monocultures at the farm level. Akrofi-Atitianti et al. (2018) or Pérez-Neira (2016b) introduce in this comparison the existing differences between organic vs conventional management. Recent publications investigate the energy productivity of labor (Pérez-Neira et al., 2020, 2023) or the food-energy-water nexus in young cocoa plantations (Armengot et al., 2021). A much smaller number of studies evaluate the economic viability of the crop, estimating monetary indicators (income, costs, net margin, labor productivity, etc.) to allow the comparison of different management practices (Seufert et al., 2012; Armengot et al., 2016). Also noteworthy are those investigations that assess the cocoa/chocolate life cycle showing how cocoa production and processing/packaging are the main environmental hotspots (GHG emissions, acidification, energy, water, etc.) (Recanati et al., 2018; Miah et al., 2018; Bianchi et al., 2021; Boakye-Yiadom et al., 2021; Awafo and Achaw-Owusu, 2022). In Ecuador, particularly in the coastal region of Guayas, Pérez-Neira (2016a) and Pérez-Neira et al. (2020b) quantify cumulative energy demand and other impact categories for chocolate production, while Pino et al. (2013) and Pérez-Neira (2016b) estimate the profitability as a function of different management. More recently, Avadí et al. (2021) and Avadí (2023) present a very complete evaluation of the economic and environmental performance (using LCA) of the Ecuadorian cocoa value chain, distinguishing various types of systems in each of its phases (i.e. the various types of farming systems, processing and distribution).

In the Ecuadorian Amazon, Vasco et al. (2021) focus their analysis on the drivers of fertilizer and pesticide expenditure in the north of the region; Tennhardt et al. (2022) explore the social and economic co-benefits of environmentally friendly cocoa farms; while Gray and Bilsborrew (2020) analyze stability and change within indigenous land use. Through a case study, Caicedo et al. (2022b) compare the environmental and economic impact of organic and conventional AFS in the Ecuadorian Amazon, while Torres et al. (2022) evaluate the carbon sequestration capacity of chakras with cocoa. So far, the most complete economic and environmental assessment (using LCA) of cocoa production in the Amazon can be found in Avadí et al. (2021) and Avadí (2023). Based on disaggregated data from INEC corresponding to ESPAC 2018, these authors propose a new typology of agricultural producers (small subsistence producer, small micro-entrepreneur producer, medium and large producer) that they analyze in depth for each of the three Ecuadorian regions (Coast, Highlands and Amazon). These studies also provide extensive information on the value sub-chains and the environmental impact according to the varieties grown, the cultivation systems, etc.

Even with this important background, it is possible to state that research evaluating the economic and environmental performance of cocoa production in the Ecuadorian Amazon is still scarce and, to the best of our knowledge, there are no previous studies investigating the heterogeneity of management styles linked to cocoa production on smallholders in the region from a bottom-up approach. This may be due, among other reasons, to the difficulty, high costs and complex logistics associated with the fieldwork required to answer these questions. But, at the same time, this gap in the literature limits our scientific ability to make assertions about the functioning of cocoa production in this territory. Consequently, the objective of this work is twofold: a) to evaluate the aggregate energy and economic metabolism of smallholder cocoa producers (< 10 ha) in the Ecuadorian Amazon and b) to investigate the existing differences in the technical-economic management cropping styles. For this purpose, primary information was collected from a statistically representative sample of the cocoa area managed by smallholders. Based on this information, a life cycle assessment (LCA) methodology (Environmental Footprint, EF 3.0) (Zampori and Pant, 2019) was used and a cost-benefit analysis was performed. Management styles and their characterization were performed using hybrid hierarchical k-means clustering. Additionally, the importance of making visible the productive management styles that make economic yields compatible with low environmental impacts is discussed as a starting point for the promotion and upscaling of agroecology in Amazonian cocoa production, since upscaling will necessarily involve the commitment of different social and political actors.

2. Materials and methods

2.1. Case study and collection of primary information

This study was conducted in three provinces in the north-central Ecuadorian Amazon: Napo, Orellana and Sucumbíos, which have an average annual rainfall of 3000 mm, temperatures between 25 and 32 °C and altitudes between 250 and 800 m above sea level (Climate-Data.org, 2022). These areas represent 98 % of the harvested area in the Ecuadorian Amazon. (ESPAC, 2022). For our analysis, information was obtained from 279 smallholder cocoa producers from 86 communities of the six cocoa associations: Tsatsayaku, Kallari, Wiñak, Asosumaco, San Carlos and Aprocel, which were randomly selected from the total number of affiliated members and whose location is represented in Fig. 1. The farms were selected with the support of field technicians from the Amazon Central Experimental Station, which is managed by the National Institute for Agricultural and Livestock Research (INIAP), as well as agricultural extension agents from the Ministry of Agriculture and Livestock of Ecuador and the associations of cocoa producers in the region.

Face-to-face questionnaires were used with smallholder farmers (<10 ha of cocoa) to collect the primary information needed for the LCA inventory and cost-benefit analysis. The fieldwork was conducted during one year, between March 2020 and March 2021. To improve the quality of the information, since most of the interviewed farmers do not have production records, it was contrasted with information available from associations and/or other primary sources (technical, INIAP reports, statistics, etc.). In total, 561 ha of cocoa crops were covered, representing 1.4 % of the area managed by smallholders (<10 ha) in the three provinces (ESPAC, 2022). The sample size corresponds to a margin of error of 5.0 %, for a confidence level of 95 % under simple random sampling, which justifies the validity of the data to establish overall behaviors of the area that is managed by smallholder cocoa farmers: approx. 82.3 % of the area of the crop in production, i.e. 40,000 ha (ESPAC, 2022).

2.2. Environmental and economic assessment of cocoa production in the Ecuadorian Amazon

2.2.1. System boundaries, functional unit and inventory

Following the recommendations of the LCA (ISO, 2006), system boundaries were defined according to a cradle-to-gate approach. The units used to carry out the analysis were mainly three: ha, kg of cocoa, and kg of production sold (cocoa + other products such as cassava, banana, etc.). Environmental impacts were estimated by accounting for direct consumption of materials and energy associated with cocoa management, also incorporating indirect impacts associated with inputs related to the environmental cost of producing and transporting inputs (fertilizers, crop protection, tools, etc.) used in farm management. A mass criterion was followed for the allocation of environmental burdens. In this way the impacts were distributed in two different ways: a) all the impacts were allocated to cocoa as the main crop; b) they were distributed between cocoa and the production sold.

Based on the primary information gathered from the 279 questionnaires, an inventory was carried out where, in addition to food production, the main inputs used in the production process were classified into five categories (see Table S1): a) Fertilization: manure, organic fertilizers such as biols, and synthetic chemical fertilizers (N, P, K and Ca); b) Crop protection: the main herbicides, pesticides and/or fungicides used, either conventional or organic; c) Supplies (petroleum derivatives): including the main energy consumption (gasoline, diesel or electricity, in some cases, for cocoa drying or irrigation systems) and petroleum derivatives such as the oil used in the weeders; d) Machinery and tools: inventory of the main machines (mainly brush cutters) and tools used in management, such as machetes, clothing, gloves, sprayers, etc. The useful life of each machine and tool was estimated and amortized during their time of use in each production system based on Armengot et al. (2021); e) Human labor: the time spent in the agricultural activity of harvest and post-harvest, as well as fertilization, weed management, etc., was counted. For the economic analysis, a distinction was made between paid and unpaid work, most of which was performed by family members.

2.2.2. Energetic metabolism, carbon footprint and other environmental impacts during farm operations

Based on the environmental footprint methodology (EF version 3.0), 16 impact categories were calculated based on Eq. (1). SimaPro software and the ecoinvent 3.8 databases were used. For the presentation of the results and discussion, the impacts associated with energy and carbon footprint (CF) have been prioritized. The remaining impact categories (14) are summarized in Table S2, S3 and S4 of the supplementary materials. Carbon sequestration and emissions associated with land use change were not considered in the CF. The efficiency of energy use was derived from the indicators NR EROI (Eq. (3)), for which the energy output was previously estimated (Eq. (2)) (Tyedmers, 2000). Finally, the L EROI (Eq. (4)) was calculated to measure the energy return (edible biomass) in relation to the accumulated demand for labor (CEDL), defined as the sum of human labor plus the consumption of non-renewable energy on the farm that reduces/complements the agricultural work on the farm (machinery, fuels, etc.) calculated from Pérez-Neira et al. (2020b).

$$\mathbf{EI_i} = \sum \mathrm{I_{(j)}} \times \mathrm{C_{(i,j)}} \tag{1}$$

$$\mathbf{EO} = \sum \mathrm{D_{(c)}} \times \alpha_{(c)} + \sum \mathrm{BC_{(f)}} \times \alpha_{(f)} \tag{2}$$

$$\mathbf{NR\ EROI} = \mathrm{EO/CED} \tag{3}$$

$$\mathbf{L\ EROI} = \mathrm{EO/CEDL} \tag{4}$$

In the above equation: $\mathrm{EI_i}$ = Environmental impact of the category *i* (where i = NR CED (Non-renewable cumulative energy demand; CF (Carbon footprint); OD (Ozone depletion); IR (Ionizing radiation); PO (Photochemical ozone formation); PM (Particulate matter); HTnc (Human toxicity, non-cancer); HTc (Human toxicity, cancer); AC (Acidification); EUfw (Eutrophication, freshwater); EUm (Eutrophication, marine); EUt (Eutrophication, terrestrial); ECfw (Ecotoxicity, freshwater); LU (Land use); WU (Water use) and RU (Resources use, minerals and metals) (RU); $\mathrm{I_{(j)}}$ = Input *j* (where *j*: fertilizers, crop protection, petroleum derivatives; machinery, tools, etc.) (different units/kg or ha); $\mathrm{C_{(i,j)}}$ = Characterization factor of impact *i* in relation to input *j*, which allows aggregating and homogenizing the releases (impact per unit); EO = Energy output (MJ/ha); $\mathrm{D_{(c)}}$ = Dry cocoa (kg/ha); $\alpha_{(c)}$ = Energy coefficient of dry cocoa (MJ/kg); $\mathrm{BC_{(f)}}$ = By-crop *f* (f = banana, cassava, etc.) (kg/ha); $\alpha_{(f)}$ = Energy coefficient of by-crop *f* (MJ/ha); NR EROI = Non-renewable EROI; L EROI = Labor EROI; CEDL = Cumulative energy demand for labor (MJ/ha), computed as the sum of human labor energy plus the consumption of non-renewable energy on the farm that reduces/complements the agricultural work on the farm (machinery, fuels, etc.)

2.2.3. Cost-benefit analysis of on-farm cocoa management

To investigate the economic dimension, a cost-benefit analysis of cocoa farm management was carried out (Jaibumrung et al., 2023): a) Income (In) from the sale of cocoa and other co-products (cassava, bananas, etc.) was estimated and, b) Total costs (TC) were assessed as the sum of expenditure on fertilization, crop protection, supplies (petroleum derivatives: diesel, oil, electricity), expenditure on machinery and tools depreciated according to their useful life (Armengot et al., 2021) and other costs (which represent very small amounts), as well as salaried work. Both basic quantities and prices were obtained from the questionnaires. The net margin (NM) was used as a proxy for crop profitability (Eq. (5)), and labor productivity (LP) as defined by Eq. (6), and efficiency in generating farm net income (Eq. (7)) were also obtained. Furthermore, two ecoefficiency indicators were calculated: energy intensity (USD net margin per MJ) (Eq. (8)) and emissions intensity (CO2-eq/USD net margin) (Eq. (9)).

$$\mathbf{NM} = \sum \mathrm{In} - \sum \mathrm{TC} \tag{5}$$

$$\mathbf{LP} = \mathrm{NM/L} \tag{6}$$

$$\mathbf{EEco} = \mathrm{NM/In} \times 100 \tag{7}$$

$$\mathbf{EI} = \mathrm{NM/NR\ CED} \tag{8}$$

$$\mathbf{CF\ I} = \mathrm{CF/NM} \tag{9}$$

In the above equations: NM = Net Margin (USD/ha); $\mathrm{In_{(f)}}$ = Income derived from the sale of cocoa and by-crops (USD/ha); TC = Total cost (USD/ha) (which includes expenditure on fertilizers, crop protection, supplies including diesel, oil, etc. and paid labor); LP (USD/h) = Labor productivity; L = labor (h/ha) (which includes both paid and unpaid work, mainly family work); EEco = Economic efficiency; EI = Energy intensity (USD/MJ); CF I = Carbon footprint intensity (kg $\mathrm{CO_2}$-eq/USD)

2.3. Statistical analysis and characterization and technical-economic classification of cocoa production in the Amazon region

As mentioned above, data have been collected from 279 farms with a total area of 561 ha of cocoa cultivated, which is not evenly distributed among them. Consequently, the size of each farm was used as a weight in the calculation of the mean and the other statistics. Since the observed variables are not normally distributed, mainly due to the presence of a high degree of skewness and several extreme values, bootstrapping was used to estimate the confidence intervals for the mean and total values for the Ecuadorian Amazon smallholder cocoa producers. Bootstrapping is a statistical procedure that resamples a single data set with replacement to create many simulated samples, allowing the calculation of standard errors or confidence intervals that are asymptotically more accurate than the standard intervals obtained using the sample variance and the assumption of normality (which is not met) (DiCiccio and Efron, 1996). Specifically, the bias-corrected and accelerated bootstrap (BCa) is the chosen method to construct the confidence intervals from the bootstrap distribution of 10,000 replications, using the weighted mean as the estimator. The BCa approach adjusts for both bias and skewness in bootstrap distribution and is accurate in a wide variety of settings, producing reasonably narrow intervals (Efron, 1987).

For the technical-economic characterization of farming styles, different variables have been considered, particularly: yields, income, fertilizer use, crop protection, supplies -where energy is included-, consumption of tools and machinery, (family and/or paid) labor, total costs, economic efficiency and the net margin of cocoa and of the farm as a whole (including the sale of co-products). In order to establish a classification of the farms, cluster analysis was applied. Cluster analysis is the name given to a group of statistical multivariate techniques whose main objective is to group objects (in our case, farms) on the basis of their characteristics in such a way that units within a cluster exhibit high similarity to each other, while being distinctly dissimilar from units in other clusters (Hair et al., 1998). Recent examples of the usage of cluster analysis in this field can be found in Ghisellini et al. (2016) or Boulestreau et al. (2022). Most common clustering methods can be classified into hierarchical and non-hierarchical but, like Ghisellini et al. (2016), the approach we have followed is a combination of both to gain the benefits of each (Hair et al., 1998) through an algorithm called hybrid hierarchical k-means clustering (Kassambara, 2017). In this algorithm, the number of clusters and their centers are determined by the hierarchical clustering (using Euclidean distance and Ward linkage), and then this information is fed into a k-means clustering to produce the final clusters. All analyses were performed using R statistical software v.4.2.1 and the following packages: tidyverse (v.1.3.2), boot (1.3–28), modi (v.0.1.0) and factoextra (v.1.0.2).

3. Results

3.1. *Energetic and economic metabolism of cocoa production in the Ecuadorian Amazon*

On average, the farms analyzed have 2.0 ha are cocoa; 93.5 % in AFS and 7.5 % in monoculture (see Table 3). 23 % of the farmers use fertilizers or synthetic chemicals, which is why they are called "conventional" farms. The remaining 77 % do not use synthetic chemicals to manage their agroecosystems, i.e., they follow organic management (certified or uncertified), but only 22 % of them are certified organic. 63 % of respondents were Kichwa and 37 % were Mestizo. The most cultivated cocoa varieties were Nacional (47 %), Super-tree (28.8 %), CCN51 (17.3 %) (Trinitarios) and INIAP (5.9 %). In our sample, there are no farmers with technical irrigation. Table 1 summarizes the energy and economic metabolism associated with smallholder cocoa producers in the Ecuadorian Amazon. Total production in the area (40,000 ha) was estimated at 34.9 thousand tons of food (841 kg/ha on average, and particularly, 289 kg/ha of cocoa). This production amounted to 307.8 TJ (7692 MJ/ha) in the form of edible energy, 72.7 % of which was cocoa, 5.8 % by crops for sale in the market, and 21.5 % by crops not sold (self-consumption, family networks, etc.). This production generated a total income of USD 23.38 million (584 USD/ha), 93 % of which came from cocoa. On the input side, the energy consumption was estimated at 56.4 TJ (1409 MJ/ha), with the use of fertilizers (67 %) and petroleum derivatives (10.9 %) being the inputs with the greatest weight on the total (Fig. 2). The economic analysis shows a TC of 4.3 million USD (107.5 USD/ha), with the sum of fertilizers and tools and machinery accounting for 72 % of the total. On the other hand, labor accounted for 15.4 % of production costs and 4.7 % of the energy consumption.

The NR CED and CF of producing 1 kg of cocoa was estimated at 4.18 MJ and 0.98 kg CO_2 -eq; 3.47 MJ and 0.75 kg CO_2-eq if all the production sold is considered in the analysis (Table 2). In terms of efficiency, the NR EROI of cocoa was 24.9, which means that, for each unit of non-renewable energy introduced into the system, >24 are obtained in the form of cocoa. In economic terms, the NM generated by the sale of cocoa and other by-crops in the entire Amazon region was estimated at USD 19.07 million (476 USD/ha) with cocoa being the most important output. Crossing the environmental and economic dimension, the EI of sold production was estimated at USD 2.19 NM for each MJ of NR CED, which implied emissions of 0.39 kg CO_2 -eq for each USD NM (CF I). Likewise, labor productivity (LP) was estimated at USD 3.6 per hour worked and economic efficiency (EEco) at 78.8 %. Tables S2, S3 and S4 show the remaining environmental impact categories analyzed (AC, PO, etc.) per hectare, kg of cocoa and kg of production sold.

3.2. *Technical-economic characterization and management typologies in Amazonian cocoa production*

Based on their differences in technical and economic management, the cluster analysis described above found three clusters of smallholder cocoa farmers. The dendrogram in Fig. 3 (above) shows the agglomeration process of the hierarchical clustering, where each farm starts as its own cluster and is successively grouped by similarity until all observations form a single cluster, showing that three is an appropriate number of clusters in terms of stability since the height of each joining indicates the dissimilarity between clusters. The scatter plot in Fig. 3 (below) shows the observations, colored by cluster according to the final k-means solution, represented on the two first dimensions (accounting for >60 % of the total variance in the data) obtained by principal component analysis. A convex hull for each cluster is also plotted, showing a complete separation between clusters. Table 3 presents a characterization of each of the three clusters (number of farms, ethnicity, surface areas, cropping systems, etc.), Table S1 presents the detailed inventory of inputs and outputs used for the environmental and economic analysis by cluster and Tables S2, S3 and S4 also show the environmental impact

Table 1
Energy and economic metabolism of smallholder cocoa production in the Ecuadorian Amazon (average estimates per ha and total -over 40,000 ha).

Individuals/units	Energy				Economic			
	MJ/ha		TJ		USD/ha		USD × 10^6	
	Estimate	95 % CI	Estimate	95 % CI	Estimate	95 % CI	Estimate	95 % CI
A) Output (i + ii + iii)	7692.4	[7093; 8401]	307.8	[283.7; 336.1]	584.3	[524.8; 650.7]	23.4	[21.0; 26.0]
i. Cacao	5592.8	[4999; 6293]	223.8	[200.0; 251.8]	542.9	[485.1; 609.3]	21.7	[19.4; 24.3]
ii. By-crops (sold)	448.7	[328.3; 611.2]	18.0	[13.1; 24.5]	41.4	[30.9; 55.6]	1.7	[1.2; 2.2]
iii. By-crops (non-sold)	1650.9	[1541; 1744]	66.0	[61.7; 69.8]	–	–	0.0	–
B) Inputs (i + … + v)	1409.6	[1051; 2266]	56.4	[42.1; 90.7]	107.5	[91.2; 129.6]	4.3	[3.6; 5.2]
i. Fertilization	944.0	[613.5; 1892.1]	37.8	[24.5; 75.7]	39.9	[26.9; 60.4]	1.6	[1.1; 2.4]
ii. Crop Protection	146.4	[106.9; 197.8]	5.9	[4.3; 7.9]	7.9	[5.6; 11.1]	0.3	[0.2; 0.4]
iii. Petroleum derivatives	154.1	[114.5; 206.5]	6.2	[4.6; 8.3]	5.1	[3.7; 6.9]	0.2	[0.1; 0.3]
iv. Tools and machinery and other cost	98.9	[94.4; 103.8]	4.0	[3.8; 4.2]	38.0	[34.5; 41.6]	1.5	[1.4; 1.7]
v. Labor	66.3	[60.2; 72.7]	2.7	[2.4; 2.9]	16.6	[12.2; 22.4]	0.7	[0.5; 0.9]

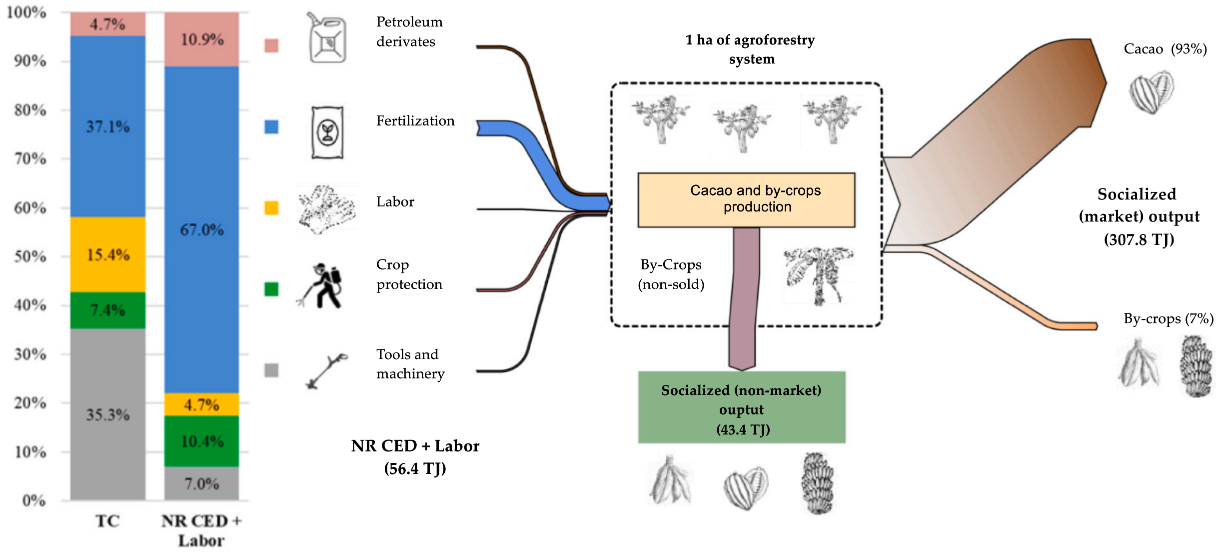

Fig. 2. Energy metabolism of cocoa production on smallholder farms in the Ecuadorian Amazon (total -over 40,000 ha).

Table 2
Indicators of environmental and economic efficiency in cocoa production in the Ecuadorian Amazon (different units; (*) = total -over 40,000 ha).

Indicators	Unit	Value	
a. Energy and CF		Estimate	95 % CI
NR CED	TJ (*)	53.8	[39.7; 87.8]
	MJ/ha	1343	[995; 2193]
	MJ/kg cocoa	4.18	[3.3; 6.7]
	MJ/kg sold production	3.47	[2.7; 6.1]
CF	Mt CO_2-eq (*)	8.16	[6.8; 711.5]
	kg CO_2-eq/ha	203.9	[169; 287]
	kg CO_2-eq/kg cocoa	0.98	[0.8; 1.3]
	kg CO_2-eq/kg sold production	0.75	[0.7; 1.0]
NR EROI cocoa	Cocoa	24.9	[21.0; 30.3]
NR EROI sold production	–	27.8	[23.5; 33.3]
L EROI	–	15.6	[14.0; 18.2]
b. Economic			
i. Cocoa			
Net Margin	USD × 10^6 (*)	17.42	[15.4; 19.7]
	USD/ha	435.4	[385.9; 493.4]
EI	USD/MJ	2.19	[1.8; 2.7]
CF I	kg CO_2-eq/USD	0.47	[0.2; 0.7]
ii. Sold production (cocoa + by-crops)			
Net Margin	USD × 10^6 (*)	19.07	[17.0; 21.4]
	USD/ha	476.8	[424.9; 536.2]
LP	USD/h	3.61	[3.2; 4.2]
EEco	%	78.85	[75.3; 81.6]
EI	USD/MJ	2.46	[2.2; 3.0]
CF I	kg CO_2-eq/USD	0.39	[0.1; 0.6]

categories analyzed (AC, PO, etc.) per hectare, kg of cocoa and kg of production sold by cluster.

The first and largest cluster (C1) (67.3 % of the sample) concentrates those farmers (71 and 29 % Kichwa and Mestizo) who barely manage their cocoa farms, following a strategy that could be called almost “harvesting”. 89 % of the farms in this group do not use synthetic chemicals, although only 22 % of them are certified organic. The remaining 11 % use synthetic chemical fertilizers or plant protection products very occasionally and not systematically. The average area of this group is 2.0 ha per farm and the most frequent varieties were Nacional (50 %), Super-tree (25.7 %) and CCN51 (16 %). C1 is the group with the lowest yields (177 kg/ha), total LP (3.37 USD/h) and profitability (cocoa and total net margins are 268 and 304 USD/ha, respectively). However, in terms of energy efficiency including by-crops, the results show higher figures than the C3, i.e., a NR EROI around 22.5 (Fig. 4). The second cluster (C2) represents 12.9 % of the sample and is composed of organic farmers (100 %), mostly Kichwa (94.5 %), who do not use synthetic chemicals and manage their small farms (1.3 ha on average) culturally. 47.2 % of these farms are certified organic and produce mostly national fine aroma cocoa (80 %). C2 farmers minimize external monetary expenses by not relying on external inputs, however, they obtain higher yields and MN than in C1 due to a more systematic management of AFS (maintenance pruning, integrated pest management, etc.). C2 is the cluster with the highest total economic-environmental efficiency with a CF I of 0.29 kg CO_2-eq/USD and a total labor productivity twice that of the other two clusters: 8.73 USD/ha. C2 is also the cluster with the lowest environmental impact in all categories and functional units assessed (Table S2, S3 and S4).

Finally, the third cluster (C3) (the remaining 19.8 %) is mainly composed of conventional farms (76 %) of an average size of 2.7 ha of cocoa managed mostly by mestizo farmers (84 %). This is the most management intensive cluster, with higher total costs and cocoa yields per ha (565 kg/ha). The main varieties grown are Super-tree (50 %) and CCN51 (30 %). Its NM is the highest of the three groups (815 and 863 USD/ha considering cocoa and all crops, respectively). In terms of energy efficiency, C3 obtains a NR EROI of 14.8 and a total CF I of 0.93 kg CO_2 -eq/USD. Within C3 there are a small number of farms (24 %) that carry out good organic management (fertilization, cultural work, etc.). If we compare these results with the average behavior of the sample (Fig. 5), we observe how if all farms behaved like conventional farms in cluster 3, cocoa production would increase by 93 %, reaching a NM (sold production) 75 % higher than the current one. However, this intensification of production would increase the environmental impact of management and decrease economic/energy efficiency. For example, the NR CED and CF I indicator would increase by 117 and 21.8 % respectively. If cluster 2 organic production were the dominant management, cocoa production would remain more or less constant and NM would increase by 29 %, making economic labor productivity 141 % higher than the current average. At the same time, in environmental terms, NR CED and CF I would be reduced by approximately 90 and 70 %. However, if the management of the organic farms in cluster 3 were scaled up, the MN could be increased to conventional C3 levels but without compromising environmental outcomes.

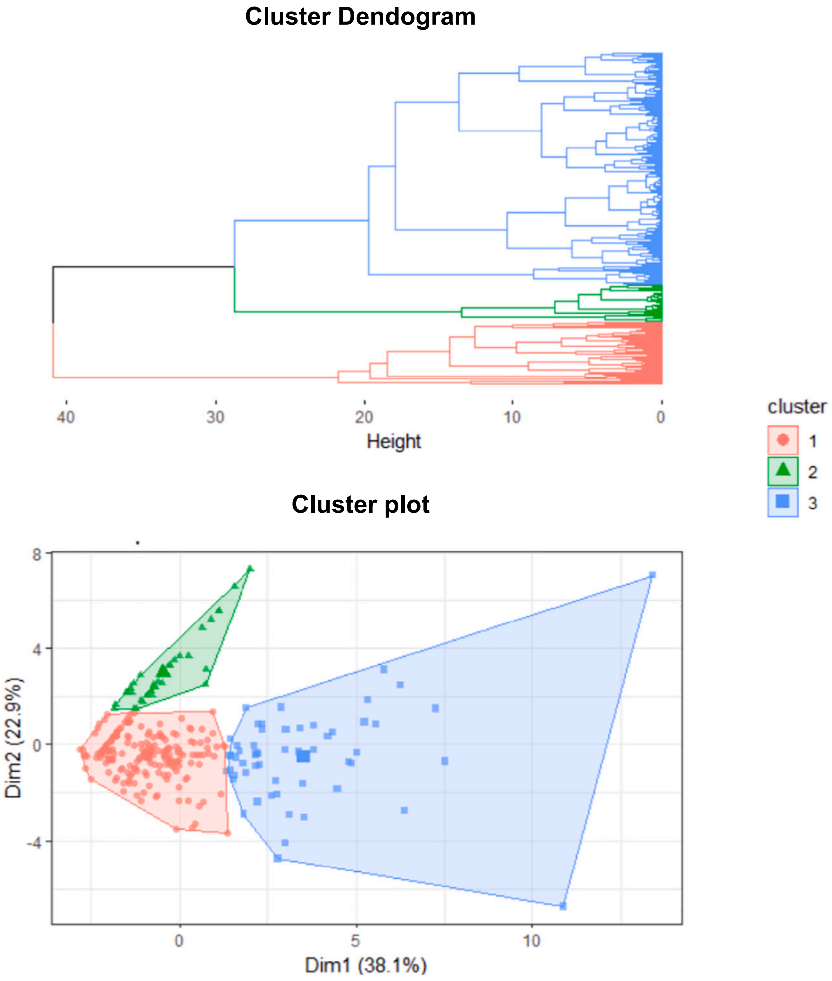

Fig. 3. Cluster dendrogram and cluster plot of cocoa production in the Ecuadorian Amazon.

Table 3
Main characteristics of farms according to cocoa management styles in the Ecuadorian Amazon.

Particulars	Unit	Total	Cluster 1	Cluster 2	Cluster 3
Farm characteristics					
i. Farms	N	278	188	36	55
ii. Ethnicity					
Kichwa	%	63.3	71.1	94.4	16.4
Mestizo	%	36.7	28.9	5.6	83.6
iii. Surface area					
Cacao	ha per farm	2.0 (±1.6)	2.0 (± 1.6)	1.3 (±1.3)	2.7 (±1.7)
	ha	522.7	367	46.7	147.2
AFS	% ha	93.5	94.6	97.0	89.7
Monoculture	% ha	6.5	5.4	3.0	10.3
iv. Cacao varieties					
CCN51	% ha	17.8	16.3	6.9	30.1
INIAP	% ha	5.9	7.8	0.0	3.0
Nacional	% ha	47.5	50.2	79.9	17.3
Super-tree	% ha	28.8	25.7	13.2	49.6
>1 variety on the farm	% farms	15.0	13.4	5.6	25.5
v. Use synthetic chemicals	% farms	22.7	11.2	0.0	76.4
vi. Organic certification	% farms	22.6	21.9	47.2	7.3

4. Discussion

4.1. Economic and environmental impacts of cocoa production in the Ecuadorian Amazon

Our study shows how smallholders in the Ecuadorian Amazon produce cocoa mostly in low intensive AFS where family labor is the main input (Vera et al., 2020; Jadan et al., 2012; Ntawuruhunga et al., 2023). This result, which is congruent with Torres et al. (2022), suggests that public statistics may be underestimating the presence of these types of systems in the region. There seems to be a consensus that Amazonian AFS have low cocoa yields, which translates into low income. If the average yield in Ecuador for the Amazon is estimated at 360 kg/ha (ESPAC, 2022), our study reports a lower yield for smallholders (260 kg/

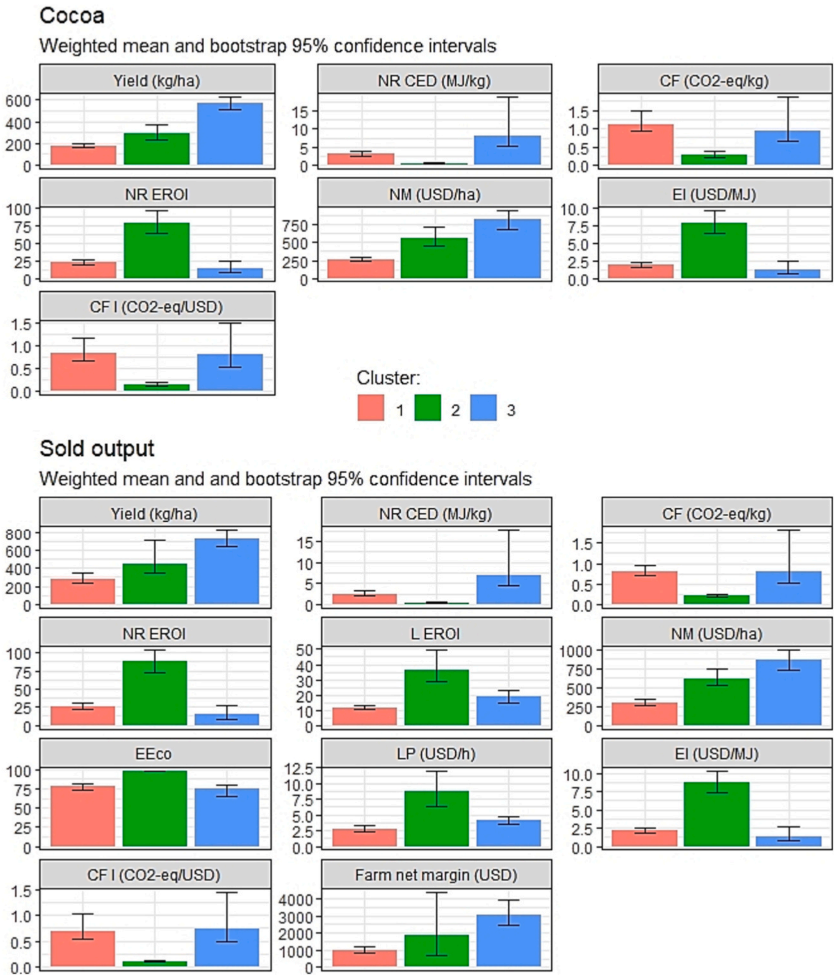

Fig. 4. Carbon footprint, energy consumption and economic-environmental indicators by cluster.

ha). Despite spending little on inputs and having high economic efficiency (EEco), farmers obtain modest margins (391 USD per ha), especially when compared to conventional monocultures on the Ecuadorian coast (approx. 2000 USD/ha) (Pérez-Neira, 2016b; Avadí et al., 2021) which, however, have much lower economic efficiency due to high input costs, in addition to a higher dependence on non-renewable energy (NR CED) and other environmental impacts (Utomo et al., 2016; Pérez-Neira, 2016b; Viteri and Toledo, 2020; Parra-Paitan and Verburg, 2022). Avadí et al. (2021) estimate an average profit for small subsistence cocoa farmers and micro-entrepreneurs in Ecuador of 500 USD and 2500 USD. Our work yields intermediate results (1600 USD) but with a large dispersion in the data due to, among other factors, differences in average farm size and management style (see Section 3.2). At the aggregate level, the estimated MN for the 40,000 ha represents 11.7 % of the estimated profit for smallholder cocoa production in Ecuador (89 % of the crop area is in the hands of smallholders).

The vast majority of farmers in these AFS sell bananas or cassava in local markets, thus generating additional income, but the main destination of the co-products is self-consumption and/or exchange in family/local networks (see Fig. 3). These cultural practices do not generate income, but reduce expenses and contribute to the autonomy and food security of the communities where producers are inserted (Jianbo, 2006; Jacobi et al., 2015). In this sense, our study has not been able to capture the full productive potential associated with these cocoa AFS. For example, Armengot et al. (2021) or Pérez-Neira et al. (2023) estimate how the production of co-products per ha can be substantially higher than that of cocoa. Therefore, there is a part of the food production (not quantified) that is not harvested that could improve the food autonomy of the producing families and their communities and/or be sold in alternative economic circuits to obtain higher incomes per ha. The low dependence on external inputs and non-renewable energy found in our research means that the environmental impacts associated with Amazonian cocoa are lower than those obtained in previous studies. For example, Pérez-Neira (2016b) or Armengot et al. (2021) estimate a NR CED of 7.4 and 4.8 MJ/kg of cocoa for conventional AFS in the Ecuadorian coast and Bolivia respectively, while Utomo et al. (2016) obtain a CF comprised between 0.39 and 0.81 kg CO_2-eq in Indonesia. Our values are even lower than those obtained by Avadí (2023) for smallholder cocoa farms in the Amazon (< 5 ha) (NR CED between 5.8 and 7.9 MJ/kg cocoa), which points to a lower dependence on external inputs. On the other hand, it should be noted that in AFS, the energy productivity of labor (L EROI) is significant and high labor productivity/efficiency has positive synergies with food security (Altieri et al., 2011). An L EROI higher than 5 implies that the production systems analyzed are able to generate sufficient energy surpluses for an extended reproduction of labor in energy terms (see Marco et al., 2020; Padró et al., 2019) as is the case in Amazonian cocoa AFS whose L EROI was estimated between 14.7 and 20.4.

4.2. *Styles of management in Amazonian cocoa and the need for public policies for the upscaling of agroecology*

Our results show that smallholder cocoa farmers follow at least three different management styles. Each of these styles responds to a differential logic when organizing production and provides different economic and environmental results (van der Ploeg and Ventura, 2014).

Fig. 5. Comparison of profitability results, energy consumption, carbon footprint and eco-efficiency indicators of cluster 2, cluster 3 (conventional) and cluster 3 (organic) farms with average results. Indicators with an asterisk (*) refer to cocoa, while the others refer to production sold.

Organic management of AFS —C2 and C3 (organic)- are the most energy efficient (NR EROI), have lower CF per kg of cocoa (and others environmental impatcs); and achieves the highest economic efficiency (EECo) and return on labour (LP). These results are in line with previous studies showing how organic farming, especially based on agroecology: 1) reduces its dependence on non-renewable energies (Smith et al., 2015; Seufert et al., 2012) and 2) allows similar or even higher income in terms of labor productivity than conventional management (Armengot et al., 2016; van der Ploeg et al., 2019; Caicedo et al., 2022a, 2022b). There are strong reasons to support the hypothesis that agroecological agriculture can drive a technical-economic model able to generate incomes comparable to, if not higher than, those of conventional monoculture (van der Ploeg et al., 2019). This potential lies in the confluence of two reasons: a) the higher net margin to income ratio (EEco) and b) the volatile off-farm prices that imply a constant increase in costs and a squeeze on income (ib.). The effects derived from “peak oil” (Arizpe et al., 2015) and the current energy crisis (IEA, 2022) may exacerbate this trend, causing an imperative need to upscale agroecological practices (MAG, 2018; FAO, 2018; Sabourin et al., 2018). This is why food sovereignty social movements have been proposing different agroecology upscaling strategies to accompany and facilitate processes that enable a sustainable agrarian transition that also improves the income capacity of farming families (FAO, 2018; Gliessman, 2019).

The objective pursued could focus, for example, on the dissemination of successful farm management - such as organic farms in cluster 3 - among the largest possible number of farmers in the territory (outscaling) together with the implementation of public policies and institutional strategies that facilitate these processes (upscaling) (Rosset and Altieri, 2017; González de Molina, 2013; Tittonell, 2019). Some “bottom-up” strategies that have been implemented in other territories have been: The dissemination of good management practices from “agroecological beacons” (Nicholls and Altieri, 2018), “farmer-to-farmer” processes (Holt-Giménez, 2006) or agroecology schools (Mier et al., 2018; Rosset et al., 2019). From a scientific approach, some of the challenges may be related to strengthening agroecologically based agronomic research and promoting participatory action research processes (producers, associations and other institutions) in the areas of cocoa production, post-harvest and profitability (INIAP, 2021; Caicedo et al., 2022b). Currently, there are some agroecological cocoa scaling initiatives in the Amazon at the farm level led by NGOs, provincial and local organizations, including the participation of academia and research institutes (GADPN, 2017; Chakra Corporation, 2022). However, these initiatives are limited and there is a need for food policies that address, among other issues: specific regulatory aspects, better access to value markets (the differential price of the organic market is not working as an economic incentive -see Avadí et al., 2021), distribution policies, marketing, storage of cocoa itself as a resource access policy, consumer awareness, valuation of eco-system services and/or strengthening of territorial organizations (Le Coq et al., 2020; Avadí et al., 2021; Ntawuruhunga et al., 2023).

4.3. *Limitations and future research*

This work has some limitations that we would like to point out:

a) There is an economic and environmental potential related to coproducts in AFS that needs to be further assessed (Armengot et al., 2021), as well as other economic aspects related to supply chains and sub-supply chains to be explored (market possibilities, transformation, etc.) (Avadí et al., 2021); b) Complete CF calculations for each management style found including, for example, emissions from harvest residues (INIAP, 2021), carbon sequestration capacity of the systems and the effects of land use change (LUC) (Torres et al., 2022); c) As discussed in Avadí (2023), by incorporating carbon sequestration in the CF calculations, emissions per ha and kg can be negative. This type of analysis may open the debate on valuation and economic compensation for the maintenance of multiple ecosystem functions associated with AFS (see: Jadan et al., 2012; Lewandrowski et al., 2014; Vera et al., 2019; Niether et al., 2020; Purnomo et al., 2021), including carbon sequestration; d) including the social and political dimension of sustainability in the analyses as a prerequisite to know the cultural and institutional barriers to change (Calle et al., 2013; Rosset and Altieri, 2017; Sullivan-Wiley and Teller, 2020; Copena et al., 2022) as well as the gender perspective (De Marco Larrauri et al., 2016; Reigada et al., 2021) and e) To investigate and explain the apparent discrepancies between official statistical data and those obtained in this and other studies on the Amazonian cocoa (Torres et al., 2022). All these and other limitations are raised as future lines of research.

5. Conclusions

This research presents an analysis of the energy and economic metabolism of smallholder cocoa production management in the Ecuadorian Amazon. The results show how cocoa production in the Ecuadorian Amazon is highly energy efficient and has a relatively low carbon footprint (and other environmental impacts) compared to other crop management systems. However, low yields lead to low profitability which is one of the main critical points in the region. In addition, three different styles of crop management have been identified in this work. The results show how some farmers conventionally intensify their production thus increasing their net margin and, at the same time, their dependency on external inputs and the environmental impact. On the other hand, there is a small group of small farmers who manage their AFS based on good organic/agroecological practices. These farms, which perhaps could be “agroecological beacons” in the Amazon, combine income with reduced environmental pressure. In line with Ecuador’s constitutional objectives of food sovereignty and good living, public policies that contribute to the upscaling and improvement of good agroecological practices should be implemented to increase the income of small farmers while guaranteeing the environmental and economic sustainability of the Amazonian territory.

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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.08.005.

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