Journal of Cleaner Production 304 (2021) 126941

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Food-energy-water nexus of different cacao production systems from a LCA approach

Laura Armengot [a, *], María J. Beltrán [b], Monika Schneider [a], Xavier Simón [c], David Pérez-Neira [d]

[a] International Cooperation Department, Research Institute of Organic Agriculture, FiBL, Switzerland
[b] Department of Economics, Pablo de Olavide University, Seville, Spain
[c] Department of Applied Economy, FCEE, University of Vigo, Vigo, Spain
[d] Department of Economy and Statistics, University of León, León, Spain

ARTICLE INFO

*Article history:*
Received 5 November 2020
Received in revised form
24 March 2021
Accepted 30 March 2021
Available online 9 April 2021

Handling editor: Bin Chen

*Keywords:*
Food-energy-water nexus
LCA
Agroforestry
Organic farming
Sustainability

ABSTRACT

This study presents an evaluation of the food-energy-water nexus (FEWn), complemented by a thorough life cycle assessment (LCA), of four young cacao production systems: two full-sun monocultures and two agroforestry systems under conventional and organic management. Land footprint (LF) for food production, non-renewable cumulative energy demand (NR CED) for energy, total water footprint (TWF) for water, and three efficiency indicators for the FEWn were all analysed. In addition, ten LCA impact categories were evaluated in relation to two functional units (kilograms of cacao output and kilograms of total crop output, i.e., cacao + other crops). The integrated analysis of the FEWn and the LCA framework reveals how agroforestry systems and organic management report better environmental performances for almost all indicators and impact categories considered, except for the TWF. However, given that the systems analysed have no irrigation, between 96.3% and 99.8% of the TWF corresponds to green water, i.e., soil moisture from precipitation. Green water has lower environmental impacts and opportunity costs than the water used to manufacture inputs ($WF_{input}$). Accordingly, when the efficiency of the nexus is measured in relation to the $WF_{input}$, organically managed systems produce more food/energy per unit of water used. Our results show how production diversification and organic and cultural management practices can improve energy efficiency and reduce the use of water associated with the inputs and, consequently, improve the nexus, as well as the rest of the environmental impacts analysed. The design of agricultural policies focused on sustainability should strongly favour the establishment of agroforestry systems, particularly those that are organically managed.

## 1. Introduction

In the context of food production, agriculture accounts for 70% of the global freshwater withdrawals, making it the largest user of water. In addition, the food production and supply chain absorbs about 30% of the globally consumed energy (FAO, 2011). As a result, agriculture is reported to have a huge impact on the environment (Foley et al., 2005, 2011), greatly contributing to biodiversity loss, climate change, and changes in the global nitrogen cycle. Hence the need for more sustainable farming systems (Rockström et al., 2009; Campbell et al., 2017). In this sense, humanity is currently facing the major challenge of guaranteeing an abundant supply of food, energy resources and water, while minimising environmental degradation as part of the sustainable development objectives (Liu et al., 2018). The food-energy-water nexus (FEWn) is useful to study the connection between these three elements, together with the synergies, trade-offs and conflicts that arise from their management, as well as to quantify the links between the nexus nodes and promote different social, economic and environmental goals (Liu et al., 2017; Zhang et al., 2019; Ji et al., 2020). In recent years, research on the FEWn has substantially increased, as proved by the number of research and review papers on this topic (see Arthur et al., 2019; Ghodsvali et al., 2019; Wiegleb and Brunssuggest, 2018).

Among the tools used to analyse the nexus, life cycle assessment (LCA) is one of the most important ones (Al-Ansari et al., 2015,

---

* Corresponding author
*E-mail address:* laura.armengot@fibl.org (L. Armengot).

https://doi.org/10.1016/j.jclepro.2021.126941

**Acronyms**

| | |
|---|---|
| AC | Acidification |
| AD | Abiotic depletion |
| CA | Conventional agroforestry |
| CM | Conventional monoculture |
| CWR | Crop water requirements |
| EROWI | Energy return on water investment |
| EO | Energy Output |
| EU | Eutrophication |
| FEWn | Food-energy-water nexus |
| FWE | Freshwater ecotoxicity |
| GWP | Global warming potential |
| HT | Human toxicity |
| LCA | Live cycle assessment |
| LF | Land footprint |
| MAE | Marine water ecotoxicity |
| NR CED | Non-renewable cumulative energy demand |
| NR EROI | Non-renewable energy return on investment |
| OA | Organic agroforestry |
| OD | Ozone layer depletion |
| OM | Organic monoculture |
| PO | Photochemical oxidation |
| TE | Terrestrial ecotoxicity |
| TWF | Total water footprint |
| W/E intensity | Water/energy intensity |
| WF | Water footprint |
| $WF_{crop}$ | Water footprint of the crop |
| $WF_{input}$ | Water footprint of the inputs |

2017; Salmoral and Yan, 2018). LCA enables understanding the interconnection and feedback relationships between the nexus and other environmental impact categories from a ‘cradle-to-grave’ perspective. It is an internationally acknowledged methodology that evaluates the main hotspots, compares production alternatives (or management alternatives, in the case of agriculture) and identifies opportunities for improvement (Notarnicola et al., 2017; Coltro and Karaski, 2019). In addition, LCA is a powerful tool for guiding production and political decision-making processes, as well as for planning possible lines of action (Seidel, 2016; Salas et al., 2017). Policy design and decision making are among the most recurrent concerns in debates around the FEWn (Bieber et al., 2018; Dargin et al., 2019; Rising et al., 2020; or Yu et al., 2020). Some studies have focused on estimating the geographical dimension of the FEWn and LCA at different scales (De Laurentiis et al., 2016; Pei-Chiun and Hwong-wen, 2020), the role of diet (Batlle-Bayer et al., 2020) or that of water pumping systems (Pradeleix et al., 2015), among other examples. However, despite the acknowledgement and potentiality of linking FEW nexus analysis and LCA, the number of empirical studies on specific products carried out from this approach is limited. Irabien and Darton (2015) analysed the production of greenhouse tomato, Martínez-Hernández et al. (2019) and Litskas et al. (2019) that of orange peels and medicinal and aromatic plants, respectively, while Leivas et al. (2020) focused on spirit drinks and assessed the critical points and the strategies for improvement.

Cacao is a major export commodity for many tropical countries. About 5.3 million tonnes of dry cacao beans were produced worldwide in 2018 on 12 million hectares (FAOstat, 2020) mainly managed by smallholders (Hütz-Adams et al., 2016). While the global demand for cacao is growing, productivity is declining in many producing areas due to aged plantations, degraded soils, pests and diseases (Flores and Sarandón, 2004). In addition, climate change is threatening the production of cacao (Schroth et al., 2016). As a result, the agricultural frontier is expanding at the expense of massive deforestation (Raschio et al., 2017). On the other hand, cacao is traditionally cultivated under forest-canopy or agroforestry systems, but full-sun monocultures are being promoted to increase production in the short-term (Armengot et al., 2016). In monocultures, labour and locally-produced inputs are being replaced with a large number of external inputs (synthetic fertilisers, herbicides and pesticides, fuels, electricity, oils, etc.) and machinery, thus contributing to increase the environmental pressure of those systems (Emmerson et al., 2017).

Organic farming is often proposed as an alternative to reduce the impacts of agriculture (Badgley et al., 2007). However, the usually lower yields of organic farming compared with conventional agriculture (Seufert et al., 2012; Meier et al., 2015) can outweigh the environmental benefits per product unit (Tuomisto et al., 2012; Seufert and Ramankutty, 2017). On the other hand, agroforestry systems have been reported to contribute to climate change mitigation through increased carbon sequestration, to climate change adaptation by buffering climate extremes (Jacobi et al., 2015; Blaser et al., 2018), and to food security, among other environmental, social and economic benefits (Cerda et al., 2014; Niether et al., 2020).

Despite the importance of cacao, no previous works have analysed its FEWn, and studies that compare types of production management from an LCA perspective are also rare. For instance, Vesce et al. (2016), Recanati et al. (2018) or Miah et al. (2018) have assessed the life cycle of cacao/chocolate by impact category (global warming potential, cumulative energy demand, eutrophication, etc.) and chocolate variety. These authors showed how the on-farm production of raw materials and/or the manufacture of chocolate are the phases of the cycle with the highest environmental impact (for almost all categories), but they did not provide disaggregated information by type of management. Other LCA studies, like those by Steiger (2010) or Pérez-Neira et al. (2020b), focused on the carbon footprint and emphasised how organic chocolate, in contrast with conventional chocolate, reduces most impacts. At the on-farm level, Utomo et al. (2016) analysed the global warming potential, acidification and eutrophication of cacao production in Indonesia by types of management (agroforestry vs. monoculture), while Pérez-Neira (2016b) and Pérez-Neira et al. (2020a) studied energy efficiency in Ecuador and Bolivia. Mekonnen and Hoekstra (2010) estimated the global average water footprint of cacao, while Ortiz-Rodríguez et al. (2015) and Naranjo-Merino et al. (2018) did it for the case of Colombia. More recently, Bianchi et al. (2020) have included cumulative energy demand and water consumption among the eight impact categories considered in their ‘cradle-to-grave’ analysis, although they have not explored their nexus in depth.

On the basis of these precedents, the present study compares the FEWn of four cacao production systems, i.e., two full-sun monocultures and two agroforestry systems under conventional and organic management during the first five years after their establishment. The analysis of the FEWn is complemented by the evaluation of ten LCA impact categories. The joint assessment of the FEWn and the life cycle of food, energy and water in these production systems enables us to understand the complex links that bind them and to determine their main ‘hotspots’ for the purpose of contributing to technical and political decision-making processes.

## 2. Material and methods

### 2.1. Boundaries, functional units and inventory

This study was carried out in Bolivia and presents the life cycle assessment (ISO, 2006) from a 'cradle-to-farm gate' approach of four types of cacao production management: (1) agroforestry under conventional management (CA); (2) agroforestry under organic management (OA); (3) full-sun monoculture under conventional management (CM) and (4) full-sun monoculture under organic management (OM). We used two functional units: one associated with the cacao output (1 kg of cacao) and one with the total crop output (1 kg of cacao, banana and other crops). Empirical data were collected during the first five years (2010–2014) at a new and experimental cacao plantation. Each production system was replicated four times in a completely randomised block design, with a plot size of 48 m × 48 m. In the agroforestry system plots, cacao trees grew together with bananas, plantains, timber trees, palm trees, and other fruit trees, including avocado, rambután, copoazú, asaí and achachairú trees (see Niether et al., 2018 for a complete list of the tree species and the planting density data). In the monoculture plots, plantains were planted to protect the cacao trees from direct sunlight during the first years, but they were removed in 2012, following local practice.

In the conventionally managed plots, agrochemicals were used. Weeds were controlled by means of brush-cutters and herbicides (mixed with adherents), with 4–5 applications per year. Pesticides were only occasionally applied to control leaf-cutting ant plagues. A synthetic fertiliser called Blaukorn BASF (12-8-16-3 $N-P_2O_5-K_2O-MgO$) was applied twice per year around the cacao trees, spread on the soil at a distance of 1–1.5 m from the stem. Foliar applications (Super Foliar 20-20-20) were made once a year. In the organic plots, a leguminous perennial cover crop (*Neotonia wigthii*) was planted for weed control, but *machetes* and brush-cutters were also used when needed. Compost was prepared using biomass from the surroundings of the trial site as well as purchased woodchips and/or rice shells. Only cacao trees received fertiliser applications, with the agroforestry systems, both the conventionally and the organically managed plots, receiving half the dose used in monocultures.

From 2010 to 2014, yield and input data were collected and estimated per hectare. Yields included cacao and other harvested crops, mainly bananas and plantains. The amount of active substance of the herbicides, adherents and insecticides applied in each plot was also recorded. The amounts of fuel and oil were estimated according to the total time of use of brush-cutters and their theoretical consumption ($l\ h^{-1}$). An inventory of all the materials and tools implemented during the trial (e.g., brush-cutters, pruning material, spraying material, cacao harvesting trays) was made. The useful life of each tool was estimated and amortised over their time of use in each production system and plot, e.g., that of the spraying material in relation to the litres applied, that of the harvesting trays based on the total number of kilograms produced, that of the pruning shears according to the total pruning time, etc. This way, using data drawn from the inventory, we measured the impacts associated with the inputs and capital goods used in the different production systems.

### 2.2. Food-energy-water nexus

#### 2.2.1. Land footprint and energy analysis

In order to calculate the land footprint, the direct demand for land per unit of product was considered, as shown on Equation (1). As regards the energy analysis of the various cacao production systems, it was performed in two steps. First, the energy output (EO) was quantified from Equation (2). The EO refers to the energy contained in the food produced on farms. Although this indicator is subject to discussion (Fluck, 1979; Guzmán and González de Molina, 2015), it is nevertheless widely used to assess the energy efficiency of crops (Hercher-Pasteur et al., 2020). Subsequently, the non-renewable cumulative energy demand (NR CED) was estimated from Equation (3), taking into account the use of direct energy (used on the farm), indirect energy (the energy cost of producing the inputs used on the farm) and capital (amortisation of the energy cost of producing tools and machinery). The coefficients required to calculate the energy output were taken from Moreiras et al. (2005) and Pérez-Neira et al. (2020a), while the NR CED was estimated by implementing the CML-IA baseline methodology version 3.05, and using the Ecoinvent 3.5 and Agribalyse 3.0 databases with SimaPro software.

$$\mathrm{LF} = \mathrm{Y}^{-1} \tag{1}$$

$$\mathrm{EO} = \sum \mathrm{D}_{(c)} \times \alpha_{(c)} + \sum \mathrm{BC}_{(i)} \times \alpha_{(i)} \tag{2}$$

$$\mathrm{NR\ CED} = \sum \mathrm{I}_{(j)} \times \beta_{(j)} \tag{3}$$

In the above equations: LF = Land footprint; Y= Yield ($t\ ha^{-1}$); EO = Energy output ($MJ\ ha^{-1}$); $D_{(c)}$ = Dry cacao ($kg\ ha^{-1}$): $\alpha_{(c)}$ = Energy coefficient of dry cacao ($MJ\ kg^{-1}$); $BC_{(i)}$ = By-crop *i* (banana and/or plantain) ($kg\ ha^{-1}$); $\alpha_{(i)}$ = Energy coefficient of by-crop *i* ($MJ\ ha^{-1}$); NR CED = Non-renewable cumulative energy demand ($MJ\ kg^{-1}$); $I_{(j)}$ = Input *j* (fertilisers, energy, crop protection, tools, etc.) ($unit\ kg^{-1}$); $\beta_{(j)}$ = Energy coefficient of input *j* ($MJ\ unit^{-1}$). The energy cost of producing and maintaining tools and machinery was amortised over 1–5 years according to theoretical amortisations based on the experience of the workers involved in the trial. For example, a useful life of 5 years was attributed to chainsaws, 3 years to pruning shears and plastic trays, and 1 to *machetes* and small shovels.

#### 2.2.2. Total water footprint

The total water footprint (TWF) is defined in this paper as the sum of the water footprint of the inputs used in the management of the plots (WFinput) and that of the crop (WFcrop) (adapted from Leivas et al., 2020) (Equations (4) and (5)). The $WF_{input}$ was estimated by using the aforementioned LCA software and databases and implementing the AWARE methodology version 1.02, whereas the WFcrop was calculated by applying the methodology described in *The water footprint assessment manual* (Hoekstra et al., 2011). Considering that these are farming systems with no irrigation, the $WF_{crop}$ matches the green crop water requirement (CWRgreen), which represents the total rainwater evaporated from the plots, divided by the yield of the crop during the growth period (Equation (4)) (Hoekstra et al., 2011).

$$\mathrm{TWF} = \sum \mathrm{WF}_{input} + \mathrm{WF}_{crop} \tag{4}$$

$$\mathrm{WF}_{crop} = \mathrm{CWRgreen\ x\ Y}^{-1} \tag{5}$$

In the above equations: TWF = Total water footprint ($m^3\ kg^{-1}$); $WF_{input}$ = Water footprint of the inputs used in the management of the plots ($m^3\ kg^{-1}$); $WF_{crop}$ = Water footprint of the crop ($m^3\ kg^{-1}$); CWRgreen = Green crop water requirement ($m^3\ ha^{-1}$); Y= Yield ($kg\ ha^{-1}$).

The crop water requirement (CWR) was estimated following the criteria established on *The water footprint assessment manual* and using the CROPWAT 8.0 model developed by FAO. The concept of CWR is based on the assumption that water does not limit crop growth (the ideal moisture conditions are satisfied by either rain or irrigation). Under rainfed cultivation, the CROPWAT model uses the 'non-irrigation' condition. The evapotranspiration of the crop (ETc) was calculated from Equation (6). Green evapotranspiration (ETgreen) is the volume of rainwater consumed during the production process, while blue evapotranspiration (ETblue) is the volume of surface and groundwater consumed to produce a specific good or service (Hoekstra et al., 2011). In the absence of irrigation, ETblue equals 0 and ETgreen is equivalent to the total evapotranspiration simulated by the model. ETgreen was calculated using Equation (7) and defined as the sum of the ETgreen values estimated for all periods.

$$\mathrm{ETc} = \mathrm{Kc} \times \mathrm{ET0} \tag{6}$$

$$\mathrm{ETgreen} = \min\{\mathrm{Pef}, \mathrm{ETc}\} \tag{7}$$

In the above equations: ETc = Total crop evapotranspiration (mm $\mathrm{dec}^{-1}$); Kc = Crop-specific coefficient; ET0 = Evapotranspiration of the reference crop (mm $\mathrm{dec}^{-1}$), estimated with the Penman-Montieth method, following the CROPWAT model developed by FAO; ETgreen = Green evapotranspiration (mm $\mathrm{dec}^{-1}$); Pef = Effective precipitation (mm $\mathrm{dec}^{-1}$).

Climatic data such as temperature, humidity, precipitation, wind and hours of sunlight were gathered from the station nearest to the area where the plots are located, as provided by CLIMWAT 2.0 by FAO. The crop coefficient (Kc) used to estimate the ETc of cacao was set at 1.0 for the initial crop stage, and 1.05 for the subsequent stages. The duration of the crop was assumed to be 360 days; although the cacao tree is a perennial tree, once it starts producing it yields beans all year round. Rooting depth and crop height data were empirically obtained. Yield response was considered to be 1.0, and critical depletion data were obtained from FAO (2006). Soil texture data were drawn from Niether et al. (2017), and the initial soil water deficit was assumed to be 30%.

### 2.2.3. Efficiency indicators of the food-energy-water nexus

Non-renewable energy return on investment (NR EROI) is one of the most important indicators when it comes to measuring the energy efficiency of agricultural systems, especially in relation to the use of non-renewable energy (Equation (8)). We propose to measure the efficiency of the food-energy-water nexus through an NR EROI indicator that relates energy output and water use, as indicated by Equation (9). This indicator, which we have named EROWI (energy return on water investment) can, in turn, be divided into two sub-indicators according to the WF used to measure the water impact, whether it be the total water footprint (TWF) or the water footprint of the inputs ($\mathrm{WF_{input}}$). The two sub-indicators are distinguished by the subscripts (t) or (i).

$$\mathrm{NR\ EROI} = \mathrm{EO\ x\ NR\ CED}^{-1} \tag{8}$$

$$\mathrm{EROWI\ (t\ or\ i)} = (\mathrm{EO\ x\ Y}^{-1})\ \mathrm{x\ TWF}^{-1}\ \mathrm{or\ WF}_{\mathrm{input}}^{-1} \tag{9}$$

In the above equations: NR EROI = Non-renewable energy return on investment; EO = Energy output (MJ $\mathrm{ha}^{-1}$); NR CED = Non-renewable cumulative energy demand (MJ $\mathrm{ha}^{-1}$); EROWI (t or i) = Energy return on water investment for *t* (TWF) or *i* ($\mathrm{WF_{input}}$) ($\mathrm{MJ/m^3}$); Y= Yield (kg $\mathrm{ha}^{-1}$); TWF = Total water footprint ($\mathrm{m^2\ kg^{-1}}$); and $\mathrm{WF_{input}}$ = Water footprint of the inputs used in the management of the plots ($\mathrm{m^3\ kg^{-1}}$).

## 2.3. LCA environmental impacts

In addition to the above-mentioned impacts and following the recommendations of Guinée, (2002) for all LCAs, this work assesses all the additional environmental impact categories considered in the CML-IA baseline LCIA method. Using this methodology and the above-mentioned databases and software, ten additional categories of environmental impact *i* were estimated: abiotic depletion (AD); acidification (AC); eutrophication (EU); global warming potential (GWP 100a); human toxicity (HT); ozone layer depletion (OD); photochemical oxidation (PO); terrestrial ecotoxicity (TE); freshwater ecotoxicity (FWE) and marine water ecotoxicity (MAE) Equation (10).

$$\mathrm{EI}_{(i)} = \sum \mathrm{I}_{(j)}\ \mathrm{x}\ \mathrm{C}_{(i,j)} \tag{10}$$

In the above equation: EI(i) = Environmental impact i (where i: abiotic depletion; acidification; eutrophication; etc.) (unit kg-1); I(j) = Input j (where j: fertilisers, energy, crop protection, tools, etc.) (unit kg-1); C(i,j) = Characterisation factor of impact i in relation to input j, which allows aggregating and homogenising the releases (impact unit-1). As regards tools and machinery, the environmental impact of their production and maintenance was amortised over 1–5 years.

## 2.4. Statistical analysis

All data were analysed by implementing linear mixed models. The data of all five years were accumulated. The production system was included as a fixed factor, and the block as a random factor. The data were log-transformed when necessary to meet the normality and homoscedasticity requirements. Orthogonal contrasts were fixed a priori in order to compare the levels of the production systems, as well as monocultures versus agroforestry systems, and conventional versus organic systems. All analyses were performed using R 3.2.3 (R Core Team, 2015), with the 'lme4' package for mixed models (Bates et al., 2015), and 'lmerTest' to evaluate the significance of the effects (Kuznetsova et al., 2015).

# 3. Results

## 3.1. The FEWn in cacao production systems

The energy output of the cacao production, i.e., the energy content of the cacao beans harvested, was estimated at an average of 2.2–5.6 MJ $\mathrm{ha}^{-1}$ for the period 2010–2014, whereas the total energy output of all crops ranged between 8.4 and 53.7 MJ $\mathrm{ha}^{-1}$. This means that the energy output of the cacao production accounted for 4.9% and 33.3% of the total energy output of all crops in agroforestry systems and monocultures, respectively. The land footprint per tonne of cacao was smaller in monocultures than in agroforestry systems (Table 1). Conventionally managed monocultures also had a smaller land footprint than organically managed ones, yet this difference was not observed between agroforestry systems. When considering the total crop output (cacao and other crops), the land footprint proved to be significantly larger in monocultures. The analysis of the energy indicators per kilogram of cacao showed that the NR CED was higher in conventional systems than in organic ones, while there were no significant differences between monocultures and agroforestry systems. Tools and machinery use was the item with the largest impact in most systems (Fig. 1), which shows that the cacao systems studied are not very intensive in the use of external inputs.

The TWF of the different types of management was estimated at between 13,701 and 18,990 $\mathrm{m^3\ ha^{-1}}$, and was 34.1% larger in agroforestry systems. In these production systems without irrigation, between 96.3% and 99.8% of the TWF corresponded to the $\mathrm{WF_{crop}}$, i.e., to the total rainwater evaporated divided by the yield. Therefore, the $\mathrm{WF_{input}}$ had only a minor role (Table 1). In contrast

**Table 1**
Food production, energy and water indicators, and FEWn efficiency per kilogram by production system.

| Particulars | Unit | CA | OA | CM | OM | CA-OA | CM-OM | M-A | C–O | CA-OM |
|---|---|---|---|---|---|---|---|---|---|---|
| Per kg of cacao | | | | | | | | | | |
| **1. Food production** | | | | | | | | | | |
| Land footprint | ha/t | 7.27E+00 | 8.82E+00 | 3.47E+00 | 6.88E+00 | n.s. | - | - | - | n.s. |
| **2. Energy** | | | | | | | | | | |
| NR CED | NR MJ | 4.81E+01 | 1.59E+01 | 3.99E+01 | 8.77E+00 | + | + | n.s. | + | + |
| **3. Water** | | | | | | | | | | |
| TWF | m$^3$ | 7.69E+01 | 9.31E+01 | 3.67E+01 | 7.27E+01 | - | - | - | - | n.s. |
| $WF_{input}$ | m$^3$ | 2.18E+00 | 3.21E-01 | 1.81E+00 | 1.57E-01 | + | + | n.s. | + | + |
| **4. FEWn efficiency** | | | | | | | | | | |
| NR EROI | – | 4.04E-01 | 1.22E+00 | 4.87E-01 | 2.21E+00 | - | - | + | - | - |
| EROWI (t) | MJ/m$^3$ | 2.53E-01 | 2.09E-01 | 5.31E-01 | 2.67E-01 | n.s. | + | + | + | n.s. |
| EROWI (i) | MJ/m$^3$ | 8.93E+00 | 6.06E+01 | 1.07E+01 | 1.24E+02 | − | − | + | − | − |
| **Per kg of total crop output (cacao + other crops)** | | | | | | | | | | |
| **1. Food production** | | | | | | | | | | |
| Land footprint | ha/t | 6.94E-02 | 9.02E-02 | 3.03E-01 | 7.99E-01 | - | - | + | - | - |
| **2. Energy** | | | | | | | | | | |
| NR CED | NR MJ | 5.24E-01 | 1.89E-01 | 3.88E+00 | 1.15E+00 | n.s. | + | + | + | - |
| **3. Water** | | | | | | | | | | |
| TWF | m$^3$ | 1.31E+00 | 1.69E+00 | 4.30E+00 | 1.09E+01 | n.s. | - | + | - | - |
| $WF_{input}$ | m$^3$ | 2.37E-02 | 3.81E-03 | 1.73E-01 | 2.06E-02 | + | + | + | + | n.s. |
| **4. FEWn efficiency** | | | | | | | | | | |
| NR EROI | – | 8.13E+00 | 2.18E+01 | 1.82E+00 | 6.65E+00 | - | - | - | - | n.s. |
| EROWI (t) | MJ/m$^3$ | 2.84E+00 | 2.11E+00 | 1.48E+00 | 6.18E-01 | + | + | − | + | + |
| EROWI (i) | MJ/m$^3$ | 1.80E+02 | 1.08E+03 | 4.03E+01 | 3.71E+02 | − | − | − | − | − |

The data show the average for the period 2010–2014. Comparative analysis of the statistical significance ($\mu = 0.05$) of the environmental impacts by production system: $A > B$ is represented by '+' and $A < B$ by '–'. EROWI (t) and (i) = Energy return on water investment (t = TWF, i = $WF_{input}$).

with the energy analysis, when the TWF was measured per kilogram of cacao, we now found that agroforestry and organic systems had the largest TWF due to their lower yields per hectare (Table 1). More specifically, the TWF of conventional monocultures was 52.3%–60.6% smaller than that of, respectively, conventional and organic agroforestry systems. When the total system output was considered, the TWF decreased, although the same tendency between systems remained, with the exception of the two types of agroforests, between which no differences were observed. Due to the use of chemical fertilisers, the $WF_{input}$ was always larger in conventional systems in relation to the two functional units studied (Fig. 1), as it was in monocultures when the total system output was considered.

As regards the efficiency of the FEWn, NR EROI was lower in agroforestry systems and conventional systems than in monocultures and organic systems when the cacao output was considered. When comparing the total energy output, the NR EROI was 3.5 and 2.9 times higher in agroforestry and organic systems compared with monocultures and conventional systems, respectively. The EROWI(t) was higher in monocultures than in agroforestry systems, as well as in conventional monocultures compared with organic monocultures per kilogram of cacao produced. When these indicators were recalculated in relation to the total crop output (cacao and other crops), agroforestry systems multiplied their FEWn efficiency by 2.4 compared with monocultures, but conventional systems were still more efficient than organic ones. When we focused on the impact associated with the use of inputs, we see that organic management improves FEWn efficiency, i.e., the EROWI(i) was higher than it was for conventional management in relation to the two functional units studied. This was also the case of agroforestry systems when the total energy output was considered.

### 3.2. *Additional environmental impact categories*

The results (Table 2, Fig. 2) show how, regardless of the functional unit, conventional agroforestry compared with organic agroforestry, and conventional monoculture compared with organic monoculture, as well as conventional compared with organic, have all larger impacts on all categories (with the exception of HT per kilogram of cacao and total crop output, and FWE and MAE per kilogram of total crop output for the conventional–organic agroforestry comparison). For instance, the global warming potential (GWP) of organic agroforestry and monoculture was approximately 2.5 times lower than in their conventional counterparts, while FWE and MAE were, respectively, 1.7 and 2.2 times lower. Fertilisers and crop protection are the major hotspots of conventional systems for many impact categories, including AD, TE, AC and EU. On the other hand, monocultures have similar or smaller impacts than agroforestry systems when the functional unit is 1 kg of cacao. However, when the total crop output is considered, the impacts of monocultures are between 5.1 and 8.1 times larger than those of agroforestry systems for all indicators without exception. When conventional agroforestry systems and organic monocultures are compared, we observe that the impacts are larger for the former when only cacao is considered, but smaller for all categories when the total crop output is taken into account.

## 4. Discussion

### 4.1. *Production efficiency of the FEWn in cacao farming*

Even if in recent years the number of studies on the FEWn has increased severalfold (Bieber et al., 2018; Dargin et al., 2019; Rising, 2020; or Yu et al., 2020), the discussion is still alive around the lack of scientific understanding of the nexus (Liu et al., 2018), especially in relation to the performance of specific crops and types of management. In this sense, our results prove that agroforestry systems and, particularly, those that are organically managed, are more energy-efficient, although their demand for water per kilogram of cacao produced is also higher. These results are consistent with

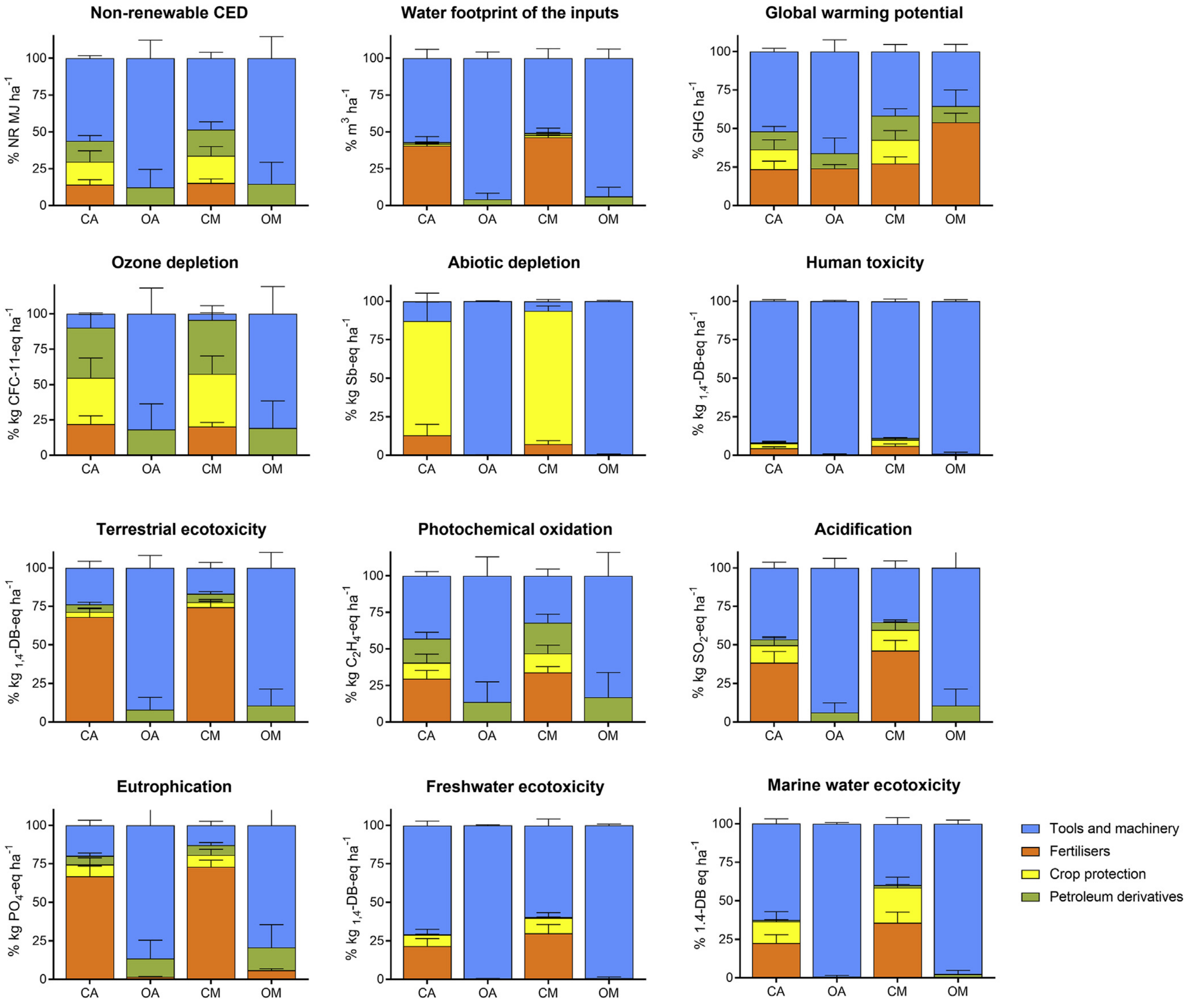

**Fig. 1.** Structure of the LCA impact categories by production system.

those of previous studies showing how, in general terms, organic production (Smith et al., 2015) and, more specifically, organic agroforestry systems enable important reductions in the use of non-renewable energy, and are consequently more energy-efficient (Pérez-Neira, 2016b; Muner et al., 2015).

In relation to the WF, no studies on cacao production had until now compared different types of management. Ortiz-Rodríguez et al. (2015) and Naranjo-Merino et al. (2018) estimated the WF—equivalent to our $WF_{crop}$—of Colombian cacao at between 13.19 and 23.23 $m^3$ $kg^{-1}$, while Mekonnen and Hoekstra (2010) reported 19.28 $m^3$ $kg^{-1}$ for the global average WF of cacao. These values are much lower than the ones obtained in the present work (ranging between 36.69 and 93.14 $m^3$ $kg^{-1}$). The differences are due to the methodology applied to calculate the WF, which puts water requirements in relation to yields, and our results show low cacao yields. The production systems studied were young plantations that had only began producing on the second year of the considered period. It is also important to note that the crop water requirements (CWR) of the systems analysed were similar; however, conventional monocultures were the ones obtaining better results in terms of $WF_{crop}$ due to larger yields. In this sense, if we focus on the yield of the last year of study (2014), we observe that the $WF_{crop}$ in conventional monocultures decreased to 21.27 $m^3$ $kg^{-1}$, a value that is closer to those of previous studies. Studying another subtropical crop, the plantain, Roibas et al. (2015) found differences, in terms of WF, in favour of conventional systems compared with organic systems due to the larger yields of the former. In relation to irrigation, Bianchi et al. (2020) estimated a larger use of water in monocultures compared with agroforestry systems: 0.007 vs. 0.0046 $m^3$ $kg^{-1}$ of dry cacao.

In our study, the interrelations between water and energy measured through the EROWI(t) seem to indicate that conventional systems are more efficient than organic ones. In other words, they use less water (TWF) for every unit of energy produced in the form of cacao. However, this result deserves some discussion. More than 95% of the TWF in our plots corresponded to the $WF_{crop}$, which is mostly green water, i.e., water coming from soil moisture after precipitation and used in evapotranspiration. Contrary to the water used to manufacture the inputs ($WF_{input}$), the $WF_{crop}$ is a water resource without a clear biophysical opportunity cost and with a smaller environmental impact. The biophysical opportunity cost is a concept very often used in energy analyses—for instance, when

**Table 2**
LCA impact categories per kilogram by production system.

| Particulars | Unit | CA | OA | CM | OM | CA-OA | CM-OM | M-A | C–O | CA-OM |
|---|---|---|---|---|---|---|---|---|---|---|
| **Per kg of cacao** | | | | | | | | | | |
| GWP | kg $CO_2$ eq | 3.74E+00 | 1.56E+00 | 2.98E+00 | 1.11E+00 | + | + | n.s. | + | + |
| OD | kg CFC-11 eq | 2.54E-07 | 7.44E-08 | 2.41E-07 | 4.94E-08 | + | + | n.s. | + | + |
| AD | kg Sb eq | 1.02E-04 | 6.09E-06 | 9.04E-05 | 2.66E-06 | + | + | n.s. | + | + |
| HT | kg 1.4-DB eq | 3.93E+00 | 3.42E+00 | 2.77E+00 | 1.26E+00 | n.s. | + | – | + | + |
| TE | kg 1.4-DB eq | 3.14E-02 | 7.54E-03 | 2.78E-02 | 3.86E-03 | + | + | n.s. | + | + |
| PO | kg $C_2H_4$ eq | 9.39E-04 | 3.38E-04 | 7.03E-04 | 1.36E-04 | + | + | n.s. | + | + |
| AC | kg $SO_2$ eq | 1.87E-02 | 6.21E-03 | 1.53E-02 | 2.90E-03 | + | + | n.s. | + | + |
| EU | kg $PO_4$ eq | 1.22E-02 | 1.79E-03 | 1.08E-02 | 8.98E-04 | + | + | - | + | + |
| FWE | kg 1.4-DB eq | 1.24E+00 | 8.90E-01 | 8.13E-01 | 3.27E-01 | + | + | – | + | + |
| MAE | kg 1.4-DB eq | 3.36E+03 | 1.90E+03 | 1.96E+03 | 5.11E+02 | + | + | - | + | + |
| **Per kg of total crop output (cacao + other crops)** | | | | | | | | | | |
| GWP | kg $CO_2$ eq | 4.08E-02 | 1.85E-02 | 2.85E-01 | 1.45E-01 | + | + | + | + | – |
| OD | kg CFC-11 eq | 2.77E-09 | 8.85E-10 | 2.30E-08 | 6.48E-09 | + | + | + | + | – |
| AD | kg Sb eq | 1.11E-06 | 7.24E-08 | 8.65E-06 | 3.49E-07 | +. | + | + | + | n.s. |
| HT | kg 1.4-DB eq | 4.29E-02 | 4.07E-02 | 2.65E-01 | 1.65E-01 | n.s. | + | + | + | – |
| TE | kg 1.4-DB eq | 3.42E-04 | 8.96E-05 | 2.66E-03 | 5.07E-04 | + | + | + | + | – |
| PO | kg $C_2H_4$ eq | 1.02E-05 | 4.02E-06 | 6.73E-05 | 1.79E-05 | + | + | + | + | – |
| AC | kg $SO_2$ eq | 2.04E-04 | 7.38E-05 | 1.46E-03 | 3.81E-04 | + | + | + | + | – |
| EU | kg $PO_4$ eq | 1.33E-04 | 2.12E-05 | 1.04E-03 | 1.18E-04 | + | + | + | + | – |
| FWE | kg 1.4-DB eq | 1.35E-02 | 1.06E-02 | 7.78E-02 | 4.30E-02 | n.s. | + | + | + | – |
| MAE | kg 1.4-DB eq | 3.67E+01 | 2.26E+01 | 1.87E+02 | 6.71E+01 | n.s. | + | + | + | - |

The data show the average for the period 2010–2014. Comparative analysis of the statistical significance ($\mu = 0.05$) of the environmental impacts by production system: A > B is represented by '+' and A < B by '–'.

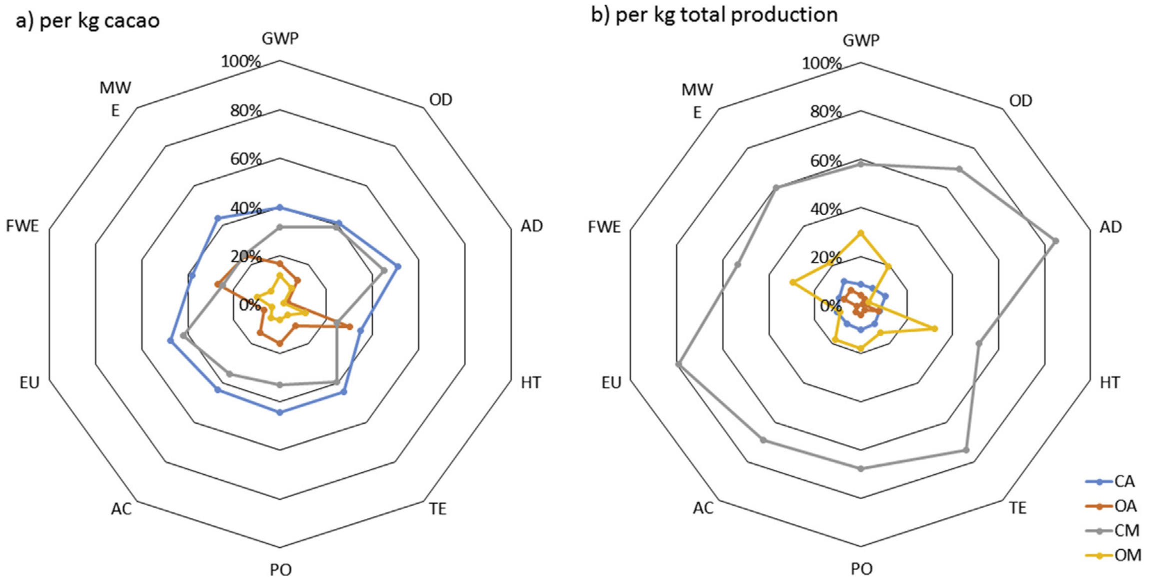

**Fig. 2.** Comparative analysis of the environmental impact by production system. The percentages represent the relative contribution of each system to the total impact of all four production systems.

solar energy flows are not considered in NR EROI evaluations because they are deemed to be cost-free—, which should be taken into account when studying the FEWn of crop farming. There is no question that both the TWF and the EROWI(t) contribute to the understanding of the nexus; however, from a technical-production perspective, indicators like the $WF_{input}$ and the EROWI(i) are better at reflecting efficiency in relation to the opportunity cost of water use in different types of management. Wichelns (2015) also underlined that considering the $WF_{crop}$ as the only parameter to estimate efficiency in the use of water might be misleading. As regards the $WF_{input}$ and the EROWI(i), agroforestry and organic systems have proved that their FEWn are more efficient in relation to the cacao output and, particularly, to the total energy output. In addition, by applying this indicator to the data published by Bianchi et al. (2020), it is possible to observe how agroforestry systems are 1.52 times more efficient than monocultures in the use of water when it comes to producing 1 MJ of cacao output in the form of cacao.

### 4.2. *Organic agroforestry systems as a production alternative*

Efficiency in the use of water and energy when producing food is critical in the search for and promotion of new agricultural practices and sustainable agrifood systems (De Laurentiis et al., 2016; Salmoral and Yan, 2018; Pradeleix et al., 2015). However, this is not the only environmental problem that agriculture will have to face in the future. For instance, the expansion of cacao monoculture farming has slowly transformed the metabolism of agricultural systems, which, in addition to putting much strain on energy and water resources, is causing loss of biodiversity, climate change, water pollution, etc. (Foley et al., 2005, 2011). In this sense, organic agriculture and agroforestry systems are usually seen as production alternatives to monoculture (Seufert et al., 2012; Meier et al., 2015). Previous studies have shown how agroforestry systems are capable of sequestering higher levels of carbon than monocultures, which is an important contribution to climate change mitigation (Jacobi et al., 2015; Blaser et al., 2018). Agroforestry systems are home to a larger number of species and greater biodiversity, and they preserve ecosystem services and provide food with higher nutritional levels (Jose, 2009; Armengot et al., 2016; Niether et al., 2020).

Along similar lines, the results of this work show how conventional systems and, in particular, monocultures have larger impacts on the LCA categories analysed, especially per kilogram of total crop output (Fig. 2). GWP is probably the environmental impact that has received more attention in academic debates, but also among consumers, enterprises and policy makers (Brodt et al., 2013; Clune et al., 2017). Some works have shown how the farming stage of cacao production may account for 40%–65% of the total GHG emissions of the agrifood system (Recanati et al., 2018; Pérez-Neira, 2016a), with values ranging between 1.71E+00 and 6.76E+00 kg $CO_2$-eq for its full life cycle (Büsser and Jungbluth, 2009; Miah et al., 2018). The values obtained in this work are comparatively higher—1.11E+00 and 3.74E+00 kg $CO_2$-eq $kg^{-1}$ of dry cacao—due to the low yields of the systems analysed. However, when the environmental burden is divided by the total crop output, the emissions per kilogram are substantially reduced (Fig. 2).

These results highlight the importance of diversifying the production of agroforestry systems. Using an LCA approach, Utomo et al. (2016) also insisted on it by studying the introduction of coconut trees in cacao agroforestry systems and the subsequent reduction of the GWP, AC or EU values in relation to those of monocultures. However, if we compare conventional agroforestry systems and organic monocultures, the data show how the former have larger impacts per kilogram of cacao produced and smaller impacts per kilogram of total crop output. On the other hand, organic monocultures considerably reduce their environmental impact by not using synthetic fertilisers or phytosanitary material, which are the most important hotspots in conventional agroforestry systems. Nevertheless, conventional agroforestry systems are usually low-intensity systems in the use of inputs (Utomo et al., 2016; Pérez-Neira et al., 2020a). Therefore, their transition to organic management is relatively easy, especially if cultural pruning practices (shape and maintenance pruning), manual weeding and organic fertilisation are intensified. It is also important to remember that, as mentioned before and in contrast with monocultures, agroforestry systems generate environmental, economic and cultural benefits that have not been evaluated in the present work (Cerda et al., 2014; Niether et al., 2020).

Finally, given their lower cacao yields, the expansion and conservation of agroforestry systems may have important trade-offs when it comes to making the objectives of environmental sustainability and production maximisation compatible (Seufert and Ramankutty, 2017). Undoubtedly, economic profitability is an important driver of change for the agricultural production and consumption model. Even though studies on this topic are still rare, works like those of Armengot et al. (2016) and Pérez-Neira (2016b) have shown how, despite their lower cacao yields, organic agroforestry systems in Bolivia and Ecuador may have similar economic performances to those of conventional monocultures because of their low production costs and/or the premium selling prices of certified organic cacao and other crops. Agricultural cooperatives play an important role in helping resource-poor farmers reach high-value markets, as well as in increasing the farmers' resilience against climate change (Donovan et al., 2017; Jacobi et al., 2015). Combining FEWn analysis and LCA can help producers improve the management of their farms and generate reliable indicators that may be used to promote their products among local and foreign consumers who support sustainable practices, and thus increase their income (Coltro and Karaski, 2019).

### 4.3. Limits and perspectives

Among the limits of the present work, we can mention that the analysis of the full cycle is not complete. In a context of food globalisation, some phases in the process, namely chocolate manufacture, commercial distribution and transportation, may contribute to reducing the environmental benefits achieved during the cacao management phase (Bianchi et al., 2020; Pérez-Neira et al., 2020b). From a methodological perspective, the use of the Ecoinvent database influences the results of the impact categories, for instance when it assumes that all pesticides applied are released in agricultural soil (Yang and Suh, 2015). In fact, Berthoud et al. (2011) analysed how, when applied, pesticides are distributed in multiple compartments (air, soil and water). These limits open the door to future researches, particularly in the direction of expanding FEWn analysis and LCA to the whole chocolate supply chain and using other methodologies that allow for greater accuracy in the analysis of impact categories, for instance, water ecotoxicity (Monteiro-Marzullo et al., 2018).

## 5. Conclusions

The integrated analysis of the FEWn within an LCA framework enables a better understanding of how the organic and agroforestry management of young plantations reports better environmental performances than conventional and monoculture management in almost all impact categories except the TWF. In production systems such as the ones here analysed, where no irrigation is applied and the $WF_{crop}$ accounts between 96-99% of the TWF, this indicator must be complemented with other impact categories, such as, for instance, the EROWI(i), which can highlight the biophysical opportunity cost of water use. The EROWI(i) shows that agroforestry and organic systems are more efficient in producing energy in the form of cacao and other crops in relation to the $WF_{input}$. Our study is the first one to report data on organic monocultures for cacao production systems. Although, as expected, they had better environmental performances than their conventional counterparts, we found that conventional agroforestry systems obtained better environmental results (for all the impact categories analysed except acidification) than organic monocultures due to the diversification of the production. In addition, since conventional agroforestry systems are usually low-intensity systems (e.g., we did not find any differences for human, marine water and freshwater ecotoxicity between both agroforestry systems), the transition to organic farming may be done without major challenges in most cases. This analytical approach should be extended to mature plantations and longer time frameworks in order to assess the long-term impacts of different production systems.

With regard to the design of agricultural policies aimed at sustainability, the results of this work indicate that policy makers should strongly promote the establishment and expansion of agroforestry systems, particularly of those that are organically managed. Production diversification, organic fertilisation and cultural management practices (pruning, land clearing, etc.) improve energy efficiency and reduce the use of water associated with the system's inputs, as well as the rest of the environmental impacts analysed. Finally, the results and discussion presented in this article invite us to reflect on the technical, production-related and political considerations of choosing agroforestry systems over monocultures and supporting public policies that promote the transition towards biodiverse and organic systems.

## CRediT authorship contribution statement

**Laura Armengot:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing & results discussion. **Ma Jesús Beltrán-Muñoz:** Formal analysis, Methodology, Writing & results discussion. **Monika Schneider:** Formal analysis, Methodology, Writing & results discussion. **Xavier Simón:** Investigation, Funding acquisition. **David Pérez-Neira:** Resources, Writing & results discussion.

## 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.

## Acknowledgments

This study was performed as part of the Syscom programme financed by the Swiss Agency for Development and Cooperation (SDC), the Liechtenstein Development Service (LED), the Biovision Foundation for Ecological Development, and the Coop Sustainability Fund.

## References

Al-Ansari, T., Korre, A., Nie, Z., Shah, N., 2015. Development of a life cycle assessment tool for the assessment of food production systems within the energy, water and food nexus. Sustain. Prod. Consum. 2, 52–66.

Al-Ansari, T., Korre, A., Nie, Z., Shah, N., 2017. Integration of greenhouse gas control technologies within the energy, water and food nexus to enhance the environmental performance of food production systems. J. Clean. Prod. 162, 1592–1606.

Armengot, L., Barbieri, P., Andres, C., Milz, J., Schneider, M., 2016. Cacao agroforestry systems have higher return on labor compared to full-sun monocultures. Agron. Sustain. Dev. 36, 70.

Arthur, M., Liu, G., Hao, Y., Zhang, L., Liang, S., Asamoah, E.F., Lombardi, G.V., 2019. Urban food-energy-water nexus indicators: a review. Resour. Conserv. Recycl. 151, 104481.

Badgley, C., Moghtader, J., Quintero, E., Zakem, E., Chappeli, M.J., Avilés-Vázquez, K., Samulon, A., Perfecto, I., 2007. Organic agriculture and the global food supply. Renew. Agric. Food Syst. 22, 86–108.

Bates, D., Machler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed effects models using lme. J. Stat. Software 67, 1–48.

Batlle-Bayer, L., Aldaco, R., Bala, Fullana-i-Palmer, P., 2020. Toward sustainable dietary patterns under a water–energy–food nexus life cycle thinking approach. Current Opinion in Environmental Science and Health 13, 61–67.

Berthoud, A., Maupu, P., Huet, C., Poupart, A., 2011. Assessing freshwater ecotoxicity of agricultural products in life cycle assessment (LCA): a case study of wheat using French agricultural practices databases and USEtox model. Int. J. Life Cycle Assess. 16, 841.

Bianchi, F.R., Moreschi, L., Gallo, M., Vesce, E., Del Borghi, A., 2020. Environmental analysis along the supply chain of dark, milk and white chocolate: a life cycle comparison. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-020-01817-6.

Bieber, N.B., Ker, J.H., Wang, X., Triantafyllidis, C., van Dam, K.H., Koppelaar, R., Shah, N., 2018. Sustainable planning of the energy-water-food nexus using decision making tools. Energy Pol. 113, 584–607.

Blaser, W.J., Oppong, J., Hart, S.P., Landolt, J., Yeboah, E., Six, J., 2018. Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. Nat. Sustain. 1, 234–239.

Brodt, S., Kramer, K.J., Kendall, A., Feenstra, G., 2013. Comparing environmental impacts of regional and national-scale food supply chains: a case study of processed tomatoes. Food Pol. 42, 106–114.

Büsser, S., Jungbluth, N., 2009. LCA of Chocolate Packed in Aluminium Foil Based Packaging. ESU-Services Ltd., Uster, Switzerland. Commissioned by German Aluminium Association (GDA) in cooperation with European Aluminium Foil Association (EAFA), Düsseldorf, Germany.

Campbell, B.M., Beare, D.J., Bennett, E.M., Hall-Spencer, J.M., Ingram, J.S.I., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J.A., Shindell, D., 2017. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. Ecol. Sco. 22 (4), 8.

Cerda, R., Deheuvels, O., Calvache, D., Niehaus, L., Sáenz, Y., Kent, J., Vilchez, S., Villota, A., Martínez, C., Somarriba, E., 2014. Contribution of cocoa agroforestry systems to family income and domestic consumption: looking toward intensification. Agrofor. Syst. 88, 957–981.

Clune, S., Crossin, E., Verghese, K., 2017. Systematic review of greenhouse gas emissions for different fresh food categories. J. Clean. Prod. 140, 766–778.

Coltro, L., Karaski, T.U., 2019. Environmental indicators of banana production in Brazil: cavendish and Prata varieties. J. Clean. Prod. 207, 363–378.

Dargin, J., Daher, B., Mohtar, R.H., 2019. Complexity versus simplicity in water energy food nexus (WEF) assessment tools. Sci. Total Environ. 650, 1566–1575.

De Laurentiis, V., Hunt, D.V.L., Rogers, C.D.F., 2016. Overcoming food security challenges within an energy/water/food nexus (EWFN) approach. Sustainability 8, 95.

Donovan, J., Blare, T., Poole, N., 2017. Stuck in a rut: emerging cocoa cooperatives in Peru and the factors that influence their performance. Renew. Agric. Food Syst. 15 (2), 169–184.

Emmerson, M., Morales, M.B., Onate, J.J., Batary, P., Berendse, F., Liira, J., Aavik, T., Guerrero, I., Bommarco, R., Eggers, S., Part, T., Tscharntke, T., Weisser, W., Clement, L., Bengtsson, J., 2017. How agricultural intensification affects biodiversity and ecosystem services. Adv. Ecol. Res. 55, 43–97.

FAO, 2006. Evapotranspiración del cultivo. Guías para la determinación de los requerimientos de agua de los cultivos. www.fao.org.

FAO, 2011. Energy-smart Food for People and Climate. Issue Paper. Food and Agriculture Organization of the United Nations, Rome.

FAO, 2020. FAOSTAT (food and agricultural organization of the united nations). http://www.fao.org/faostat/en/#home.

Flores, C., Sarandón, S., 2004. Limitations of neoclassical economics for evaluating sustainability of agricultural systems: comparing organic and conventional systems. J. Sustain. Agric. 24, 77–91.

Fluck, R.C., 1979. Energy productivity: a measure of energy utilisation in agricultural systems. Agric. Syst. 4, 29–37.

Foley, J.A., De Fries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309, 570–574.

Foley, J.A., Ramankutty, N., Brauman, K., et al., 2011. Solutions for a cultivated planet. Nature 478, 337–342.

Ghodsvali, M., Krishnamurthy, S., de Vries, B., 2019. Review of transdisciplinary approaches to food-water-energy nexus: a guide towards sustainable development. Environ. Sci. Pol. 101, 266–278.

Guinée, J. (Ed.), 2002. Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards. Springer Science & Business Media, p. 692.

Guzmán, G., Gónzalez de Molina, M., 2015. Energy efficiency in agrarian systems from an agroecological perspective. Agroecol. Sus. Food 39, 924–952.

Hercher-Pasteur, J., Loiseau, E., Sinfort, C., Hélias, A., 2020. Energetic assessment of the agricultural production system. A review. Agron. Sustain. Dev. 40, 29.

Hoekstra, A., Chapagain, A., Aldaya, M., Mekonnen, M., 2011. The Water Footprint Assessment Manual. Setting the Global Standard. Earthscan, London.

Hütz-Adams, F., Huber, C., Knoke, I., Morazan, P., Mürlebach, M., 2016. In: Se, V. (Ed.), Strengthening the Competitiveness of Cocoa Production and Improving the Income of Cocoa Producers in West and Central Africa. Bonn.

Irabien, A., Darton, R.C., 2015. Energy–water–food nexus in the Spanish greenhouse tomato production. Clean Technol. Environ. Policy 18, 1307–1316.

Jacobi, J., Schneider, M., Pillco Mariscal, M., Huber, S., Weidmann, S., Bottazzi, P., Rist, S., 2015. Farm resilience in organic and nonorganic cocoa farming systems in Alto Beni, Bolivia. Agroecol. Sus. Food 39, 798–823.

Ji, L., Zhang, B., Huang, G., Lu, Y., 2020. Multi-stage stochastic fuzzy random programming for food-water-energy nexus management under uncertainties. Resour. Conserv. Recycl. 155, 104665.

Jose, S., 2009. Agroforestry for ecosystem services and environmental benefits: an overview. Agrofor. Syst. 76, 1–10.

Kuznetsova, A., Brockhoff, P.B., Bojesen Christensen, R.B., 2015. lmerTest: Tests in Linear Mixed Effects Models. R Package Version 2.0–29. http://cran.r-project.org/package&equals;lmerTest.

Leivas, R., Laso, J., Abejón, R., Margallo, M., Aldaco, R., 2020. Environmental assessment of food and beverage under a NEXUS Water-Energy-Climate approach: application to the spirit drinks. Sci. Total Environ. 720, 137576.

Litskas, V., Chrysargyris, A., Stavrinides, M., Tzortzakis, N., 2019. Water-energy-food nexus: a case study on medicinal and aromatic plants. J. Clean. Prod. 233, 1334–1343.

Liu, J., Yang, H., Cudennec, C., Gain, A.K., Hoff, H., Lawford, R., Qi, J., de Strasser, L., Yillia, P.T., Zheng, C., 2017. Panta rhei opinions: challenges in operationalizing the water-energy-food nexus. Hydrol. Sci. J. 62 (11), 1714–1720.

Liu, J., Mao, G., Hoekstra, A.J., Wang, H., Wang, J., Zheng, C., Van Vliet, M.T.H., Wu, M., Ruddell, B., Yan, J., 2018. Managing the energy-water-food nexus for sustainable development. Energy Appl 210, 377–381.

Martínez-Hernández, E., Magdaleno-Molina, M., Melgarejo-Flores, L.A., Palmerín Ruiz, Zermeño EguiaLis, Rosas Molina, A., Aburto, J., Amezcua-Allieri, M.A., 2019. Energy-water nexus strategies for the energetic valorization of orange peels based on techno-economic and environmental impact assessment. Food and Bioproducts Processing ((117):), 380–387.

Meier, M., Stoessel, F., Jungbluth, N., Juraske, R., Schader, C., Stolze, M., 2015.

Environmental impacts of organic and conventional agricultural products. Are the differences captured by life cycle assessment? J. Environ. Manag. 149, 193–208.

Mekonnen, M.M., Hoekstra, A.Y., 2010. The Green, Blue and Grey Water Footprint of Crops and Derived Crop Products. Value of Water Research Report Series No. 47. UNESCO-IHE, Delft, The Netherlands.

Miah, J.H., Griffiths, A., McNeill, R., Halvorson, S., Schenker, U., Espinoza-Orias, N.D., Morse, S., Yang, A., Sadhukhan, J., 2018. Environmental management of confectionery products: life cycle impacts and improvement strategies. J. Clean. Prod. 177, 732–751.

Monteiro-Marzullo, R.C., Dos Santos-Matai, P.H.L., Morita, D.N., 2018. New method to calculate water ecotoxicity footprint of products: a contribution to the decision-making process toward sustainability. J. Clean. Prod. 188, 888–899.

Moreiras, O., Carbajal, A., Cabrera, L., Cuadrado, C., 2005. Tablas de composición de alimentos. Ed. Pirámide, Madrid.

Muner, L.H.D., Masera, O., Fornazier, M.J., Souza, C.V.D., de Loreto, M.D.D., 2015. Energetic sustainability of three arabica coffee growing systems used by family farming units in Espírito Santo state. Eng. Agrícola 35 (3), 397–405.

Naranjo-Merino, C.A., Ortíz-Rodríguez, O., Villamizar, R.A., 2018. Assessing green and blue water footprints in the supply chain of cocoa production: a case study in the northeast of Colombia. Sustainability 10 (1), 38.

Niether, W., Schneidewind, U., Armengot, L., Adamtey, N., Schneider, M., Gerold, G., 2017. Spatial-temporal soil moisture dynamics under different cocoa production systems. Catena 158, 340–349.

Niether, W., Armengot, L., Andres, C., Schneider, M., Gerold, G., 2018. Shade trees and tree pruning alter throughfall and microclimate in cocoa (Theobroma cacao L.) production systems. Ann. For. Sci. 75, 38.

Niether, W., Jacobi, J., Blaser, W.J., Andres, C.A., Armengot, L., 2020. Cocoa agroforestry systems versus monocultures: a multi-dimensional meta-analysis. Environ. Res. Lett. 15, 104085.

Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017. The role of life cycle assessment in supporting sustainable agri-food systems: a review of the challenges. J. Clean. Prod. 140, 399–409.

Ortiz-Rodríguez, O., Naranjo, C., García-Cáceres, R., Villamizar-Gallardo, R., 2015. Water footprint assessment of the Colombian cocoa production. Rev. Bras. Eng. Agrícola Ambient. 9 (19), 823–828.

Pei-Chiun, L., Hwong-wen, M., 2020. Evaluating the environmental impacts of the water-energy-food nexus with a life-cycle approach. Resour. Conserv. Recycl. 157, 104789.

Pérez-Neira, D., 2016a. Energy sustainability of Ecuadorian cacao export and its contribution to climate change. A case study through product life cycle assessment. J. Clean. Prod. 112, 2560–2568.

Pérez-Neira, D., 2016b. Energy efficiency of cacao agroforestry under traditional and organic management. Agron. Sustain. Dev. 36, 49.

Pérez-Neira, D., Schneider, M., Armengot, L., 2020a. Crop-diversification and organic management increase the energy efficiency of cacao plantations. Agric. Syst. 177, 102711.

Pérez-Neira, D., Copena, D., Armengot, L., Simón, X., 2020b. Transportation can cancel out the ecological advantages of producing organic cacao: the carbon footprint of the globalized agrifood system of Ecuadorian chocolate. J. Environ. Manag. 276, 111306.

Pradeleix, L., Roux, P., Bouarfa, S., Jaouani, B., Lili-Chabaane, Z., Bellon-Maurel, V., 2015. Environmental impacts of contrasted groundwater pumping systems assessed by life cycle assessment methodology: contribution to the water–energy nexus study. Irrigat. Drain. 64, 124–138.

R Core Team, 2015. R: A Language and Environment for Statistical Computing. R foundation for statistical computing, Vienna, Austria. https://www.R-project.org/.

Raschio, G., Smetana, S., Contreras, C., Heinz, V., Mathys, A., 2017. Spatio-temporal differentiation of life cycle assessment results for average perennial crop farm. A case study of Peruvian cocoa progression and deforestation issues. J. Ind. Ecol. 22 (6).

Recanati, F., Marveggio, D., Dotelli, G., 2018. From beans to bar: a life cycle assessment towards sustainable chocolate supply chain. Sci. Total Environ. 613, 64.

Rising, J., 2020. Decision-making and integrated assessment models of the water-energy-food nexus. Water Scur 9, 100056.

Rockström, J.W., Steffen, K., Noone, Å., et al., 2009. Planetary boundaries: exploring the safe space for humanity. Ecol. Soc. 14 (2), 32.

Roibas, L., Elbehri, A., Hospido, A., 2015. Evaluating the sustainability of Ecuadorian bananas: carbon footprint, water usage and wealth distribution along the supply chain. Sustain. Prod. Consum. (2), 3–16.

Salas, S., Anton, A., McLaren, S.J., Notarnicola, B., Saouter, E., Sonesson, U., 2017. In quest of reducing the environmental impacts of food production and consumption. J. Clean. Prod. 140, 387–398.

Salmoral, G., Yan, X., 2018. Food-energy-water nexus: a life cycle analysis on virtual water and embodied energy in food consumption in the Tamar catchment, UK. Resour. Conserv. Recycl. 133, 320–330.

Schroth, G., Laderach, P., Martínez-Valle, A.I., Bunn, C., Jassogne, L., 2016. Vulnerability to climate change of cocoa in West Africa: patterns, opportunities and limits to adaptation. Sci. Total Environ. 556, 231, 24.

Seidel, C., 2016. The application of life cycle assessment to public policy development. Int. J. Life Cycle Assess. 21, 337–348.

Seufert, V., Ramankutty, N., 2017. Many shades of gray. The context-dependent performance of organic agriculture. Science Advances 3.

Seufert, V., Ramankutty, N., Foley, J.A., 2012. Comparing the yields of organic and conventional agriculture. Nature 485, 229–232.

Smith, G.L., Williams, A., Pearce, B., 2015. The energy efficiency of organic agriculture: a review. Renew. Agric. Food Syst. 30, 280–301.

Steiger, N., 2010. Effect of higher product quality on environmental impact: the example of chocolate production. IED – Institute for Environmental Decisions and NSSI – Natural and Social Science Interface. http://www.uns.ethz.ch/pub/publications/pdf/1742.pdf.

Tuomisto, H., Hodg, I.D., Riordan, P., Macdonald, D.W., 2012. Does organic farming reduce environmental impacts? A meta-analysis of European research. J. Environ. Manag. 112, 309–320.

Utomo, B., Prawoto, A., Bonnet, S., Bangviwat, A., Gheewala, S.H., 2016. Environmental performance of cocoa production from monoculture and agroforestry systems in Indonesia. J. Clean. Prod. 134, 583–591.

Vesce, E., Olivieri, G., Pairotti, M.B., Romani, A., Beltramo, R., 2016. Life cycle assessment as a tool to integrate environmental indicators in food products: a chocolate LCA case study. Int. J. Environ. Health 8 (1), 21–37.

Wichelns, D., 2015. Virtual water and water footprints: overreaching into the discourse on sustainability, efficiency, and equity. Water Altern. (WaA) 8 (3), 396–414.

Wiegleb, V., Brunssuggest, A., 2018. What is driving the water-energy-food nexus? Discourses, Knowledge and politics of an emerging resource governance concept. Frontiers in Environmental Science 6, 128.

Yang, Y., Suh, S., 2015. Changes in environmental impacts of major crops in the US. Environ. Res. Lett. 10, 094016.

Yu, L., Xiao, Y., Zeng, X.Z., Li, X.P., Fan, Y.R., 2020. Planning water-energy-food nexus system management under multilevel and uncertainty. J. Clean. Prod. 251, 119658.

Zhang, P., Zhang, L., Chang, Y., Xu, M., Hao, Y., Liang, S., Liu, G., Yang, Z., Wang, C., 2019. Food-energy-water (FEW) nexus for urban sustainability: a comprehensive review. Resour. Conserv. Recycl. 142, 215–224.