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Sustainability of food security in different cacao production systems: A land, labour, energy and food quality nexus approach

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ABSTRACT

The present work analyses the sustainability of food security in cacao monocultures and agroforestry systems under organic and conventional management. Using a novel approach, we developed indicators to assess crucial dimensions of food security, including land and labour productivity, the nutritional quality of food, and their nexus with energy efficiency and consumption. Our ten-year data showed that monocultures, especially conventional ones, are more productive (in terms of land and labour) when only the main crop (cacao) is considered and energy consumption is not assessed. When all the crops produced and the demand for non-renewable energy are included, agroforestry systems are more productive (kg, kcal, proteins and fats and nutritional quality index) and more energy efficient than monocultures according to all the indicators analysed. Therefore, encouraging policies that take into consideration the positive externalities of agroforestry and organic management is crucial for the sustainability of food systems.

Most important acronyms

Acronyms	Definition
CED	Cumulative energy demand
CED_L	Cumulative energy demand of labour
EI CEDL of FQ	Energy intensity of the CED_L in relation to food quality
EI of FQ	Energy intensity associated with the quality of food
EP of Ns	Energy productivity of the nutrients
EO	Energy output
EP of food	Energy productivity of food
EROI	Energy return on investment
L EROI	Energy return on labour investment
LCA	Life cycle assessment
LF	Land Footprint
L_H EROI	Energy return on human labour investment
LI of FQ	labour intensity of food quality
LP	Labour productivity
NR CED	Non-renewable cumulative energy demand
NR EROI	Non-renewable energy return on investment
NRD	Nutrient rich diet
PF	People fed in relation to the production of food (kcal or proteins)

1. Introduction

Now that environmental problems are part of the agenda, the challenge of sustainability has become one of the main pillars of food security (Clapp et al., 2021). The discussions around sustainability have refined the traditional concept of food security, which is defined as ‘a situation where all people, at all times, have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life’ (FAO, 2006). Thus, the sustainability of food security is a growing concern across the world and its evaluation may facilitate the development of better food policies (Lo et al., 2012). The multidimensional character of both concepts makes it difficult to measure them; there is no ‘golden standard’ to do it (Vaitla et al., 2017; Skaf et al., 2021). It is therefore necessary to continue making progress in the integration of interdisciplinary approaches and methodologies that allow for a better understanding of the interrelationship of the two concepts, building on a common basis that includes their nutritional, health and environmental dimensions (Green et al., 2021). One of the main approaches to this matter focuses on the limitations in the availability of land, soil, water and other resources, particularly energy (Fajar-Putra et al., 2020; Nkiaka et al., 2021). Thus, the measurement and integrated management of the water–energy–food

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security nexus is essential to improve and secure an adequate and constant supply of food (Bergendahl et al., 2018; Arthur et al., 2019; Mahlknecht et al., 2020; Purwanto et al., 2021).

As a crucial factor for the production of food, human labour has been less analysed from this nexus approach than other elements (Nag and Gite, 2020). In biophysical terms, labour can be defined as a fundamental process through which human societies appropriate, distribute and consume a set of natural energy and material flows for the purpose of having enough energy and materials available for social reproduction (Marco et al., 2020; Patró et al., 2019). It is not surprising that the technical progress and modernization of agriculture have focused on increasing land and labour productivity (kg per ha and h) in order to cope with demographic and bioeconomic pressure (see Arizpe et al., 2015). In other words, the objective has been to increase yields per unit of area and hour of work to feed a growing population and, at the same time, free up the workforce to focus on the emerging sectors (Giampietro and Mayumi, 2000). Nevertheless, the increase of land and labour productivity in agriculture cannot be explained without the massive injection of fossil energy in the form of external inputs and capital (Giampietro et al., 1999; Fischer-Kowalski and Haberl, 2014). For instance, irrigation (water and energy) or fertilizers have a positive impact on yields, while machinery and the use of fossil fuels have a positive effect on labour productivity (Fluck, 1992; Arizpe et al., 2015).

As warned since the 1970s and 1980s, the high dependence of agriculture on energy may put at risk the viability and stability of food production (Leach, 1976; Bayliss-Smith, 1982). This is especially worrying in a context like the current one, where 'peak oil' (Murray and King, 2012) poses a real threat to the globalized agrifood system and, therefore, to food security (Pfeiffer, 2006; Taghizadeh-Hesary et al., 2019). It is urgent to advance in the development of models for the production and supply of renewable foods that can reduce dependence on fossil fuels and enable increasing land and labour productivity while improving energy efficiency (Bardi et al., 2013; Smith et al., 2015). In this sense, low-input organic or peasant agriculture—especially if agroecology-based—and agroforestry systems are presented as alternatives to industrialized monocultures (Jiambo, 2006; Altieri et al., 2011; Coulibaly et al., 2017). This is particularly important in the case of cacao, where the expansion of monocultures and the intensification of production are displacing traditional shade tree managements (Gockowski et al., 2013; Ramírez et al., 2001) and expanding the agricultural frontier to meet the increasing global demand for chocolate (Wainaina et al., 2021; FAO 2022). Both factors (production intensification and reduction of forest areas) have been identified as the main causes for the loss of biodiversity and ecosystem services (Foley et al., 2005).

In most cases, organic management allows reducing dependence on petroleum and improving the energy efficiency of crops per unit of area, although the results are less conclusive per unit of food due to the lower yields (Smith et al., 2015; Seufert et al., 2012). This has encouraged various authors to affirm that, in a sustained demand scenario, the transition to organic management may accelerate the expansion of agricultural land (Muller et al., 2017; Smith et al., 2019). In addition to diet and other factors with an impact on these issues (Aleksandrowicz et al., 2016; Poore and Nemecek, 2018), organic farms that implement agroecological management strategies (diversification, intercropping, agro-sylvo-pastoral systems, soil management measures, etc.) (Bezner-Kerr et al., 2021; Aguilera et al., 2020) can reduce the conventional–organic yield gap (Ponisio et al., 2015) and even be more productive than industrial monocultures if the total output of food is considered (Altieri et al., 2011). In particular, agroforestry systems make a better use of solar energy than monocultures and produce a wide range of food for family consumption and sale, as well as other non-edible products (Jiambo, 2006; Cerdá et al., 2014; Jacobi et al., 2015; Gama-Rodrigues et al., 2021). They are also more efficient in terms of energy (Muner et al., 2015; Filho et al., 2014) and provide a diversity of ecosystem services (positive externalities) associated with climate maintenance, carbon sinks, nutrient cycles, etc. that are not taken into consideration, from an economic point of view, in market prices (Niether et al., 2020; Wainaina et al., 2021).

At the same time, the analysis of food security cannot be reduced to estimating and comparing yields per hectare or daily calorie intakes. The micronutrients required to maintain individual, family and collective health and nutrition must also be considered (Hossain et al., 2019). In this sense, the use of dietary diversity indicators, the analysis of food spending behaviours, and other nutritional and socioeconomic evaluation measures are also necessary for a good understanding of food security (Lo et al., 2012; Yao et al., 2018; Munisamy-Gopinath, 2021; Batlle-Bayer et al., 2020). For instance, Cassidy et al. (2013) suggest assessing the 'number of people actually fed per hectare of cropland', whether in kilocalories or kilograms of proteins (see also DeFries et al., 2015). On the other hand, it is also common to use nutritional quality indicators to evaluate diets, such as, for instance, the nutrient rich diet 9.3 (NRD 9.3) index or the total nutrient rich 9 (TNR9) subscore (González-García et al., 2018; Batlle-Bayer et al., 2021). Crossing these measures with those of the environmental dimension, several authors have proposed ecoefficiency indicators with a nutritional approach (nutritional LCA) to evaluate impacts (energy, emissions, etc.) in relation to various functional utilities (proteins, fats and other essential nutrients) (Nelson et al., 2018; Martínez-Blanco et al., 2011; Notarnicola et al., 2017). Using these and other indicators, production or consumption systems may be assessed and classified according to different measures that connect the nutritional, health and environmental dimensions of food security (see McAuliffe et al., 2019) with the intention of contributing significant and useful information for the design of public policies and the optimization of management practices on farms (Green et al., 2020).

In relation to cacao, some previous research works have studied energy efficiency in relation to management (Caicedo et al., 2022; Jiambo, 2006; Pérez-Neira, 2016), while others have assessed the whole life cycle of chocolate (Recanati et al., 2018; Miah et al., 2018). Recently, some works have analysed the energy efficiency of labour (Pérez-Neira et al., 2020), or the food–energy–water nexus in young cacao plantations (Armengot et al., 2021). Despite these important precedents, none of these works have used nutrition-based functional units to estimate ecoefficiency indicators or specific measures to evaluate nutritional quality. In addition, scientific data on organic and agroforestry cacao production systems are very scarce and most of the studies on cacao production show quantitative evidence for a reference year, but do not assess more than five years. With this study we have addressed these knowledge gaps on cacao production. We have designed a methodological tool composed of different novel indicators to assess the relationship between energy sustainability and food security using a nexus approach, i.e., land, labour, energy and nutritional quality. We gathered primary information during ten years (2010–2019) from an experimental field trial where organically and conventionally managed agroforestry systems and monocultures are compared. In the food production phase, we have assessed: (a) land productivity; (b) labour productivity; (c) the nutritional quality of the food output; and (d) the nexus between those aspects and energy consumption and efficiency.

2. Materials and methods

2.1. Study case: system boundaries, functional units and inventory

This work is based on an experimental trial carried out in Sara Ana (390 m a.s.l.), Alto Beni, Bolivia. In the area of study, the average annual rainfall and temperature are 1540 mm and 26.6 °C, respectively, while the soils are Luvisols and Lixisols. The planting was finished in 2009. This study assesses four different cacao production systems over ten years after their establishment: a full-sun monoculture and an agroforestry system, both under organic and conventional management. In the organic systems the EU regulations on organic farming were applied. Each system was replicated four times in a totally randomized block-design. The size of the gross plots was 48 $m \times$ 48 m, with net plots of 24 $m \times$ 24 m. The cacao tree spacing was 4 $m \times$ 4 m (625 trees/ha) in all the systems. In both the full-sun monoculture and agroforestry system plots, plantain trees were planted together with the cacao trees at a density of 625 trees/ha to protect the small cacao trees from direct sunlight. According to traditional practices, at the end of 2011 the plantain trees were removed and were replaced by bananas only in the agroforestry systems also at a density of 625 trees/ha. In addition to the bananas, cacao trees in the agroforestry systems were combined with leguminous trees (*Inga spp*. and *Erythrina* spp.*,* 8 $m \times$ 8 m tree spacing) and timber and fruit trees (16 $m \times$ 16 m). The fruit trees were still not producing by the end of the data collection of this study. The total density of the shade trees was 304 trees/ha. Banana trees are kept in the agroforestry systems up to now although is not the common practice of the farmers. Banana trees would be removed after some years to avoid competition with the cacao trees. However, with proper management, both crops can grow together for a longer period. Banana trees are highly productive and also a good economic complement to cacao production in the agroforestry trees. As a result, the agroforestry system of this study was characterised by the combination of three main crops: cacao (c), bananas (b) and plantains (p) (agroforestry$_{\text{cbp}}$). A perennial legume cover crop (*Neonotonia wightii (Am.) Lackey*) was sown in the organically managed systems. In the conventional systems, chemical fertilizers were applied and weeding was done through the use of herbicides and a mechanical weeder. In the organic systems, compost was used and weeding was performed with a mechanical weeder. Table S1 provides the details of the inputs used in the different systems. More information about the trial design can be found in Armengot et al. (2016).

From an LCA perspective, the boundaries of the system are set by applying a cradle-to-farm approach articulated in four levels of analysis and different functional units (kg, kcal or MJ, kg of proteins or fats) associated with the production of cacao and other foodstuffs. Level 1 evaluates production in terms of commercialized edible biomass of all the foodstuffs produced by the system, including cacao and other products (banana, plantain). In level 2, the energy directly consumed by the cacao plantations (through labour, organic fertilization, weeding, etc.) is quantified, while level 3 considers the energy indirectly consumed, whether to produce the inputs used on the farm (fertilizers, pesticides, etc.), or to produce the energy directly consumed in level 2 (diesel, electricity, etc.). Finally, level 4 quantifies the amortized energy cost of producing the tools and machinery used on the farm. To carry out the analysis, data were gathered (on production, inputs applied, working time, etc.) from the net plots during ten years (2010–2019), and all figures were converted to hectares. The method used to account for the main inputs— fertilization, crop protection, tools, fuel and human labour—is synthesized in Table S1, in the Supplementary Data section.

2.2. Methodological framework for the assessment of the land–labour–energy and quality of food security nexus

In order to evaluate the nexus, a methodological tool composed of different indicators that can shed light on the relationship between energy sustainability and food security in the food production phase (Fig. 1) was designed from a multidimensional perspective and according to four fundamental aspects: (a) land productivity; (b) labour productivity; (c) the nutritional quality of the total food output; and (d) the energy cost and efficiency associated with the three previous aspects. For ease of reading, the equations used to estimate the indicators are included in the Supplementary Data section at the end of the article (S2).

2.2.1. Land and labour productivity and nutritional quality of food

In order to analyse land productivity, five indicators were selected. In addition to yield (kg/ha) and land footprint (LF) (ha/t), the following have been considered: i) energy/caloric productivity of the land according to the 'energy output' (EO), which measures the edible energy produced in 1 ha and made available to society (Fluck, 1992) (Equation S1); and ii) the number of people fed by hectare of land (kcal and proteins) ($PF_{\text{kcal or protein}}$) (Cassidy et al., 2013) (Equation S2). Labour productivity (LP) was measured using two indicators that evaluate food production (kg) and energy output (MJ) per hour of work (Equation S3). Finally, the nutritional quality of the total food output (cacao + other products) was assessed using the nutrient rich diet 9.3 index (NRD 9.3) (Drewnowski et al., 2009) (Equation S4). This indicator estimates the production of nine encouraged nutrients (proteins, fibre, calcium, iron, magnesium, potassium and vitamins A, E and C) and three discouraged nutrients (total sugar, saturated fats and sodium). The larger the amount of more-is-better nutrients and the smaller that of less-is-better nutrients, the higher the score of the NRD 9.3 index. In order to compare the different systems and homogenize the results, the NRD 9.3 index was calculated on the basis of an average production of 2000 kcal.

2.2.2. Energy efficiency and productivity of the land–labour–nutritional quality nexus

The first step towards analysing the energy efficiency and productivity of the nexus was to estimate the cumulative energy demand (CED) (ha and kg) (Equation S5). The CED includes the direct consumption of

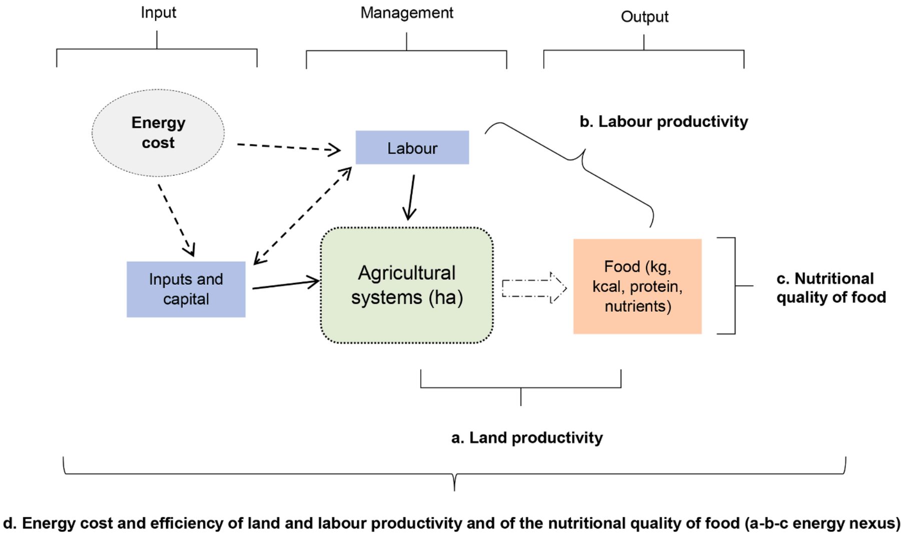

Fig. 1. Functioning scheme of the land–labour–energy and quality nexus in food production.

energy on the farm (level 2), as well as the indirect consumption, i.e., the one associated with the energy cost of producing the inputs and capital used (levels 3 and 4). Likewise, the CED is the result of adding the renewable energy (R CED) and the non-renewable energy (NR CED) used on the farm (Equation S5). As regards efficiency, the energy return on investment (EROI) (Equation S7) measures the return of energy that is intentionally invested by society in agricultural systems, while the non-renewable EROI (NR EROI) (Equation S8) emphasizes the dependence on inputs brought from outside those systems in relation to the use of non-renewable energy. In order to assess the energy productivity of the land, the following indicators were considered: i) the energy productivity of food (EP of food and cacao), which measures the production of foodstuffs (kg/ha) generated by the agroecosystem through the use of NR CED (MJ/ha) (Fluck, 1992) (Equation S9); and ii) the energy intensity of the nutrients, particularly proteins (p) and fats (f) (EP of $Ns_{(p\ or\ f)}$) (Equation S10), also in relation to the NR CED. Both indicators enable visualizing the amount of proteins and fats (kg) produced per unit of non-renewable energy (MJ) (Hirst, 1973; Weindl et al., 2020).

For the assessment of the energy efficiency of labour, two different perspectives were applied (Pérez-Neira et al., 2020). First of all, the indicator L_H EROI (Equation S11) makes it possible to measure the energy return (edible biomass) in relation to energy labour, i.e., the energy content of the food consumed by the workers to perform the required agricultural tasks. This way of measuring labour efficiency does not consider the degree of mechanization of the agricultural tasks. In other words, the extent to which labour productivity is related to the increase in the direct use of non-renewable energy on the farm—i.e., the extent to which the mechanization of tasks increases labour productivity—is not taken into account. In order to figure in this trade-off between labour and capital, the cumulative energy demand of labour (CED_L) is calculated as the sum of human labour (energy content of the food consumed by the workers) and the consumption of non-renewable energy that reduces or complements agricultural labour on the farm. From the CED_L, the energy return on labour (L EROI) was re-estimated using Equation S12.

For the purpose of evaluating the relationship between nutritional quality, labour and energy, three indicators were used: i) the intensity of energy associated with the quality of food (EI of FQ), which quantifies the consumption of non-renewable energy required to obtain 100 points in the NRD 9.3 index (MJ/100 points) (Equation S13); (ii) labour intensity of food quality (LI of FQ), which specifies the number of hours of work required to obtain the resulting NRD 9.3 score per 2000 kcal (hours/score) (Equation S14); and iii) the energy intensity of the cumulative energy demand of labour required to obtain 100 points in the NRD 9.3 index (EI CED_L of FQ) (MJ/score) (Equation S15).

2.3. Statistical analysis

The statistical analysis was performed using the R 3.6.1 software (R core team, 2015) and the packages *lme4* (Bates et al., 2015) and *lmerTest* (Kuznetsova et al., 2015) for linear mixed models, which allow including the hierarchical structure of the trial (block design) and the time series. The assumptions of normality and homogeneity of variance were checked using the residual plots, and the data were transformed with the log or square root when necessary. For the analyses of energy indicators, the data of all ten years were cumulated to meet the assumptions of the model. Production system was included in the model as a fix factor and the block as random factor. Food indicators were analysed including the production system, the year and their interaction as fixed effects, and the plot as a random effect nested within the block. The indicators NRD 9.3, EI of FQ, LI of FQ, and EI CED_L of FQ were analysed using data from the period 2012–2019, when the monocultures had lost their initial temporary shade. Only during this period is it possible to compare and identify the actual differences between monocultures and polyculture systems like agroforestry systems in terms of nutritional quantity and quality in relation to the use of energy.

3. Results

3.1. Land and labour productivity and food quality in the analysis of the food security of agroforestry production

The average yield of cacao production was highest in conventional monocultures (CM), followed by organic monocultures (OM) and the two agroforestry $systems_{cbp}$ (Fig. 2, Table 1, Figure S3). The same behaviour was observed in the energy output (EO cacao) and labour productivity (LP cacao), measured in kg and MJ of cacao per hours of work (Fig. 2, Table 1, Figure S3). During the ten years of study, monocultures produced 1.70 times more cacao (kg/ha and MJ/ha) than agroforestry $systems_{cbp}$, while conventional systems produced 1.14 times more cacao than organic ones. In other words, producing 1 t of cacao requires an average of 3.75 ha in agroforestry $systems_{cbp}$ in contrast with only 2.99 ha in organic monoculture, and only 2.27 ha in conventional monocultures. When the associated crops were considered in the calculation of land and labour productivity, agroforestry $systems_{cbp}$, on average, produced 6.08 and 4.69 times more kilograms of food per hectare and hour of work than monocultures (Table 1, Fig. 2). In average terms, agroforestry $systems_{cbp}$ produced enough kilocalories and proteins to meet the demand of 16.50 and 8.51 persons per hectare and year, respectively, in contrast with the 6.04 and 5.06 persons fed by monocultures ($PF_{(kcal\ or\ protein)}$). Likewise, the production diversification of agroforestry $systems_{cbp}$ obtained a higher score in the NRD 9.3 index per 2000 kcal.

3.2. The nexus between sustainability, food security, energy, and land productivity, labour productivity and nutritional quality

Organic systems (OM and OA) have a higher CED per hectare and per kilogram of cacao produced (Fig. 3, Table 2) than conventional systems. Fertilization accounted for 88% and 66% of the CED of OM and OA systems, while the use of petroleum derivatives (14.4 and 4.5%) or tools (13.2 and 5.2%) had a smaller share in it (Fig. 3). Organic systems used larger amounts of renewable energy that their conventional counterparts, i.e., 90.6 vs 19.9% and 73.2 vs 24.9% of the CED in monocultures and agroforestry $systems_{cbp}$, respectively. When renewable energy is not considered, conventional managements have worse results, both in terms of NR CED (per hectare and per kilogram of cacao) and in terms of energy efficiency (NR EROI) and productivity (EP of cacao) (Fig. 3, Table 2, Figure S3). In these systems, petroleum derivatives accounted for 17.6% and 20.3% of the CED, fertilization for 24% and 16.9%, and crop protection for 10.4% and 17.8% in, respectively, conventional monocultures and agroforestry $systems_{cbp}$. On the other hand, organic monocultures proved to be more productive (EP of cacao) than conventional monocultures in relation to the use of non-renewable energy: while the former produced an average of 1.6 kg of cacao per MJ of non-renewable energy, the latter only produced 0.10.

Agroforestry $systems_{cbp}$ produced 6.4 and 1.8 times more food (kg) (EP of food) and proteins (kg) (EP of $Ns_{(p)}$) than monocultures in relation to 1 MJ of non-renewable energy, while they were 3.0 times more efficient in terms of energy return (NR EROI) (Table 2). In general, organic systems obtain better results in energy return than conventional systems, although in the case of agroforestry $systems_{cbp}$ the differences between managements are not significant. In relation to the energy efficiency of labour, monocultures reach lower values than agroforestry $systems_{cbp}$ in L_H EROI, an average of 24.8 and 54.4, respectively. Including the energy that replaces or complements labour, the energy return of this factor (L EROI) is reduced to values around 5 and 11, for monocultures and agroforestry $systems_{cbp}$ respectively. The energy that replaces or complements labour accounted for 82.0% to 87.9% of the CED_L. Finally, in relation to nutritional quality and the use of energy and labour, agroforestry $systems_{cbp}$ were again more efficient than monocultures. Thus, agroforestry $systems_{cbp}$ consumed 0.12 MJ, in contrast with 0.67 MJ in monocultures, to obtain a score of 100 points in the

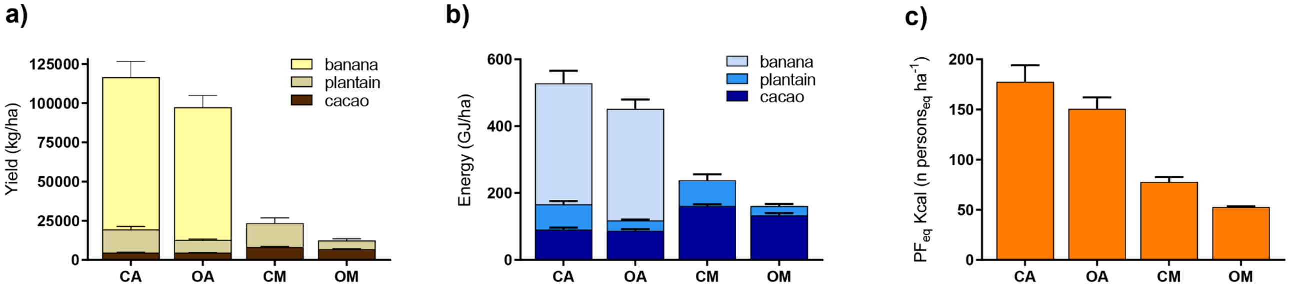

Fig. 2. a) Total system yield (cacao [dry beans] + plantain and banana [fresh weight without branches]), b) total energy output and c) per-equivalent-person consumption in relation to the production of food (PF_{eq} kcal), measured by the number of persons fed per hectare. The data show the cumulative means for the period 2010–2019. The production systems are abbreviated as follow: CA: conventional agroforestry, OA: organic agroforestry, CM: conventional monoculture, OM: organic monoculture.

Table 1

Annual mean and standard error (SE) of land and labour productivity and nutritional quality of food considering: A) only cacao yields, and B) all the crops produced by the different cacao production systems.

Indicator	Unit	CA	OA	CM	OM	
		Mean (SE)	Mean (SE)	Mean (SE)	Mean (SE)	*P*-value
A. Cacao						
A.1. Land productivity						
Yield	kg/ha	466.29 (61.29) a	447.94 (59.48) a	830.29 (102.93) b	685.69 (101.08) c	< 0.001
LF	ha/t	3.38 (0.50) a	4.12 (0.71) a	2.27 (0.53) b	3.71 (0.80) a	0.005
EO cacao	MJ/ha	9058.65 (1190.74) a	8702.10 (1155.51) a	16,130.10 (1999.6) b	13,320.85 (1963.75) c	< 0.001
A.2. Labour productivity						
LP cacao	kg/h	0.50 (0.11) a	0.46 (0.11) a	1.00 (0.21) b	0.75 (0.19) c	< 0.001
	MJ/h	9.77 (2.15) a	9.01 (2.13) a	19.52 (4.12) b	14.51 (3.70) c	< 0.001
B. Cacao and associated crops						
B.1. Land productivity						
Yield	kg/ha	11,814.47 (710.94) a	10,133.01 (778.62) a	2336.79 (516.37) b	1238.86 (169.12) c	< 0.001
LF	ha/t	0.10 (0.01) a	0.15 (0.02) a	1.27 (0.20) b	2.13 (0.38) c	< 0.001
EO total	MJ/ha	54,321.00 (3279.12) a	46,479.83 (3454.65) a	23,825.27 (2550.27) b	16,146.45 (1723.59) c	< 0.001
PF (kcal)	No. persons/ha	17.77 (1.07) a	15.21 (1.13) a	7.80 (0.83) b	5.28 (0.56) c	< 0.001
PF (protein)	No. persons/ha	9.02 (0.91) a	7.99 (0.86) a	5.74 (0.53) b	4.37 (0.56) c	0.01
B.2. Labour productivity						
LP total	kg/h	14.20 (1.06) a	10.82 (1.16) a	3.70 (1.71) b	1.63 (0.48) c	< 0.001
	MJ/h	65.25 (5.19) a	49.63 (4.96) b	33.30 (7.6) c	19.02 (3.13) d	< 0.001
B.3. Food quality index (cacao + associated crops)						
NRD 9.3*	score per 2000 kcal	702.73 (0.81)	702.66 (0.71)	672.23 (0.00)	672.23 (0.00)	

Annual means for the period 2010–2019. Different letters indicate significant differences (α = 0.05). CA: conventional agroforestry, OA: organic agroforestry, CM: conventional monoculture, OM: organic monoculture. * Data for the period 2012–2019 (see S2 for further information).

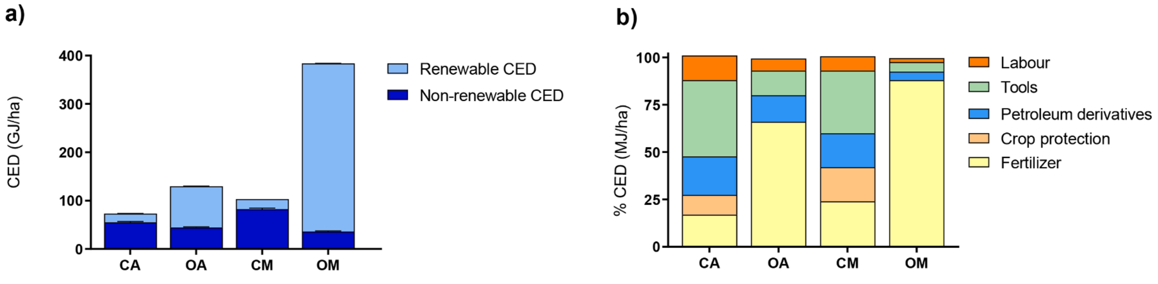

Fig. 3. a) Cumulative energy demand (CED) and energy cost structure of the inputs (%) used in the different cacao production systems. The data show the cumulative means for the period 2010–2019. The production systems are abbreviated as follows: CA: conventional agroforestry, OA: organic agroforestry, CM: conventional monoculture, OM: organic monoculture.

nutritional quality indicator (EI of FQ), and required an average of 0.44 h of work in contrast with 1.90 in monocultures, i.e., 4.4 times less time.

4. Discussion

4.1. Trade-off between productivity and food security

The present work shows how monocultures and, more specifically, conventional systems are more productive (in terms of land and labour) than the rest of management systems when only the main crop is considered (see also Armengot et al., 2016; Gockowski et al., 2013; Ramírez et al., 2001). In theory, the larger cacao yields obtained in monocultures have at least two important advantages: a) they provide higher incomes through the sale of cacao; and b) they reduce the demand for land per kilogram of cacao produced (along the lines indicated by Muller et al., 2017; Smith et al., 2019). These advantages are

Table 2
Annual mean and standard error (SE) of energy indicators and their nexus with land and labour productivity/efficiency and the nutritional quality of food for the different cacao production systems.

Indicator	Unit	CA Mean (SE)	OA Mean (SE)	CM Mean (SE)	OM Mean (SE)	*P*-value
A. Cacao						
A. 4. Energy consumption						
CED	MJ/ha	7322 (161.90) a	14,706 (1133.53) b	10,316 (245.46) c	38,392 (735.65) d	< 0.001
	MJ/kg	23.53 (3.21) a	72.79 (13.87) b	21.92 (4.6) a	129.05 (25.22) c	< 0.001
NR CED	MJ/ha	5504 (137.90) a	3946 (300.55) b	8259 (237.9) c	3625 (259.55) b	< 0.001
	MJ/kg	17.81 (2.46) a	12.72 (1.87) b	17.37 (3.56) a	9.77 (1.68) c	0.003
A. 5. Energy efficiency						
EROI	–	1.21 (0.16) a	1.06 (0.19) a	1.59 (0.21) b	0.32 (0.05) c	< 0.001
NR EROI	–	1.65 (0.23) a	1.92 (0.21) ab	2.02 (0.27) b	3.08 (0.37) c	< 0.001
EP of cacao	kg/NR MJ	0.085 (0.02) a	0.99 (0.02) ab	0.104 (0.03) b	0.159 (0.04) c	< 0.001
B. Cacao and associated crops						
B. 4. Energy consumption						
CED	MJ/kg	0.72 (0.05) a	2.31 (0.34) b	13.33 (1.96) c	78.30 (12.69) d	< 0.001
NR CED	MJ/kg	0.55 (0.04) a	0.44 (0.03) a	10.84 (1.62) b	6.32 (0.91) c	< 0.001
B. 5. Energy efficiency and land productivity, labour productivity and nutritional quality of food						
EROI	–	7.51 (0.48) a	4.75 (0.64) b	2.49 (0.32) c	0.41 (0.04) d	< 0.001
NR EROI	–	10.13 (0.7) a	12.75 (0.9) a	3.20 (0.44) b	4.55 (0.44) c	< 0.001
EP of food	kg/MJ	2.21 (0.14) a	2.81 (0.24) a	0.34 (0.09) b	0.45 (0.09) b	< 0.001
EP of Ns (p)	kg/MJ	0.04 (0.00) a	0.05 (0.00) a	0.02 (0.00) b	0.03 (0.00) c	0.025
EP of Ns (f)	kg/MJ	0.04 (0.01) a	0.05 (0.00) b	0.04 (0.01) a	0.06 (0.01) b	0.001
EI of FQ (100 points) *	MJ/score	0.13 (0.01) a	0.11 (0.01) a	0.85 (0.1) b	0.49 (0.06) c	< 0.001
L_H EROI	–	61.82 (3.42) a	47.02 (2.66) b	31.55 (4.13) c	18.02 (1.61) d	0.012
L EROI	–	12.58 (0.81) a	9.68 (0.59) a	5.78 (0.71)b	3.56 (0.33) b	< 0.001
LI of FQ (2000 kcal) *	h/score	0.40 (0.02) a	0.47 (0.03) a	1.35 (0.12) b	2.45 (0.32) c	< 0.001
EI CED_L of FQ (100 points) *	MJ/score	0.11 (0.01) a	0.13 (0.01) a	0.53 (0.06) b	0.62 (0.07) c	< 0.001

Annual means for the period 2010–2019, except for the nutritional quality of food (2012–2019, marked with *). Different letters indicate significant differences ($\alpha = 0.05$). The production systems are abbreviated as follow: CA: conventional agroforestry, OA: or ganic agroforestry, CM: conventional monoculture, OM: organic monoculture.

especially relevant in a context like the current one, where the demand for cacao is expected to keep growing (17% between 2020 and 2025, adapted from Wainaina et al., 2021, and FAO, 2022). However, if increasing profitability or meeting the demand are not the only objectives, and food security guidelines are included (Clapp et al., 2021), the data show that promoting and preserving agroforestry systems, particularly organic ones, should be a priority for the administration and other institutions (Duffy et al., 2021; Waldron et al., 2017). Agroforestry systems produce more, and more diverse, food per hectare (Ponisio et al., 2015) and unit of labour, whether for sale, self-consumption or exchange within family networks (Cerda et al., 2014; Jacobi et al., 2015), which is essential for an adequate supply of food (Muner et al., 2015; Armengot et al., 2016; Gama-Rodrigues et al., 2021).

Our work shows how production diversification not only makes it possible to obtain more food than monocultures to meet the caloric needs of more people, but also produces more proteins and macronutrients that contribute to the improvement of the nutritional quality of the farms' output. Other authors before us have used similar measures to evaluate this aspect of food security (Cassidy et al., 2013). For instance, DeFries et al. (2015) showed that 1 ha of rice or corn produces enough food to feed 19 to 24 persons, which is slightly higher than the number obtained for agroforestry $systems_{cbp}$ (between 17.8 and 15.2 persons). Nutritional quality indicators are mostly used to compare diets (González-García et al., 2018; Batlle-Bayer et al., 2020; Batlle-Bayer et al., 2021), but using them to assess the quality of food production facilitates the comparison of systems, polyculture, crop rotation and other diversification methods, for the purpose of planning actions according to production and nutritional criteria (Röös et al., 2021). However, greater diversification and higher nutritional quality of food are not necessarily rewarded in economic terms. Access to local markets, certifications or the strengthening of the cacao cooperatives may be effective strategies to improve profitability, or even match that of monocultures, through complementary income, premium prices or access to other markets (Niether et al., 2020; Armengot et al., 2016; Pérez-Neira, 2016). Still, higher incomes do not necessarily contribute to the improvement of food security, because families may choose to spend them in non-food items (Meemken, 2021).

4.2. *Energy sustainability of food security from a nexus approach*

Addressing the problem of sustainability, energy use and food security is essential to advance towards the design of systems that guarantee an adequate and constant supply of food (Mahlknecht et al., 2020; Purwanto et al., 2021). Looking ahead (to a future that is almost present), peak oil may have very significant impacts on agricultural viability. An increase in the price of energy may cause a reduction in the use of energy inputs and/or put at risk the profitability of farms that are more dependant on those resources (Taghizadeh-Hesary et al., 2019; Azpeite et al., 2015). Organic cacao farms, but also agroforestry $systems_{cbp}$, are less dependant on oil and more efficient in the use of non-renewable energy (NR EROI). Previous studies have shown how, in the case of cacao, the increase of yields in intensified systems does not compensate the higher demand for non-renewable energy (Pérez-Neira, 2016, 2020). Amongst agroforestry $systems_{cbp}$, conventional managements are more productive (in terms of land and labour), while organic ones are more energy-efficient; however, in most cases, the statistical differences are not significant. This underscores the need for a greater effort in agricultural research with an agroecological approach to improve the yields of organic agroforestry systems without negatively affecting their environmental behaviour (Seufert et al., 2012).

From a food security perspective, measuring efficiency in energy use based on the energy return provides partial results (Vaitla et al., 2017; Skaf et al., 2021), given that: a) foodstuffs may have different caloric contents; b) energy does not represent the totality of the nutritional functions of food; and c) the same caloric content may have different nutritional densities (Sonesson et al., 2017). These discussions have interesting precedents in the tradition of energy analyses and are currently key when it comes to refining the concept of food security (Hossain et al., 2019). Fluck (1992), for instance, described the boundaries of what is now called EROI and proposed using energy productivity indicators (kg/MJ) as a new measure for yields, while Hirst (1973) suggested assessing the production of proteins in relation to the use of energy (kg of proteins/MJ). In this sense, it is necessary to further deepen in the design and implementation of ecoefficiency indicators that enable the evaluation of the environmental dimension of food and food production systems in relation to their nutritional and/or health dimensions (Nelson et al., 2018; Martínez-Blanco et al., 2011; Notarnicola et al., 2017). Thus, our data show how agroforestry systems$_{cbp}$ report higher energy productivities in relation to food and proteins (EP of Food and $NE_{(p)}$), but their intensity is lower when it comes to generating nutritional quality as measured by the NRD 9.3 index.

Something similar occurs with labour. Podolinsky (2008 [1883]) was a pioneer in discussing and measuring the energy efficiency of labour in agriculture. This author stated that human beings are capable of generating, on average, 1 MJ of energy in the form of useful work after consuming 5 MJ of food, a ratio that he called 'economic coefficient'. In our methodology we used the energy embedded in the food instead of the muscle energy. According to this, the 'economic coefficient' should be higher than 1:1 in order to reproduce its own metabolism. An energy return rate above 1, in the form of edible biomass, would therefore generate sufficient surpluses to perform other 'non-productive' tasks in terms of energy. As is well known, the modernization/intensification of agriculture has increased labour productivity at the expense of greater dependence on non-renewable energy (Giampietro et al., 1999; Fischer-Kowalski and Haberl, 2014). Our data show L_H EROI values that are well above 1, which means that these systems are capable of generating energy surpluses for an extended reproduction of labour (Marco et al., 2020; Patró et al., 2019). High labour productivity (kg/ha) and efficiency (L and L_H EROI) have positive synergies with food security, especially in traditional and agroecological polyculture systems that are not very intensive in the use of non-renewable energy (Altieri et al., 2011). However, labour efficiency, as measured by L_H EROI, does not consider the replacement or complement of labour through the use of inputs and capital. L EROI includes this effect and shows, again, that agroforestry systems$_{cbp}$ report better results in this analytical dimension.

4.3. Limits and future prospects

The present work has various limitations that will turn into new lines of work in the near future: a) energy metabolism is not the only environmental dimension of sustainability, the analysis should therefore be refined by examining other impact categories linked to LCA (GHG, eutrophication, etc.) (Armengot et al., 2021) and introducing other aspects, such as ecosystem resilience (Jacobi et al., 2018); b) it is necessary to expand the analysis to the whole life cycle of cacao and its associated products (cradle-to-grave approach) (Recatati et al., 2018; Miah et al., 2018); c) food production in experimental plots does not fully respond to the logic of small farmers, who, in agroforestry systems, often grow other crops and raise small animals (hens, chickens, etc.), taking advantage of the synergies between them (Cerda et al., 2014; Gama-Rodrigues et al., 2021), a fact that should be taken into consideration; d) as banana production in the evaluated agroforestry systems$_{cbp}$ is high – in Bolivia the average banana and plantain yield is 14.9 t/ha and 11.8t/ha (FAO, 2022); a similar nexus analyses should be performed to compare the environmental performance of agroforestry systems$_{cbp}$ with cacao and banana monocultures; e) environmental–nutritional analyses need to be completed and refined by introducing other quality indicators (Hossain et al., 2019; Weindl et al., 2020); and f) addressing other socioeconomic and political aspects connected to the sustainability of food security is also recommended (Ferguson et al., 2019).

5. Final considerations

Our ten-year results evidence that the production diversification (i.e., cacao trees combined by plantains and bananas together with other shade trees) improves land productivity, labour productivity, and the nutritional quality of food, while reducing dependence on non-renewable energy and improving the productivity (kg, kcal, proteins, food quality), energy efficiency and sustainability of food security, particularly in organic systems. The present work provides a methodological tool that, by highlighting the land, labour, energy and food quality nexus, generates rigorous and easy-to-understand information on the interrelationship between the productivity/efficiency, quantity and quality of food produced in a farm. This information may be useful to compare managements and farms, or to assess production changes and make technical-production decisions about them. The nexus can also be employed to improve policies at other geographical levels (local or regional), and to promote products and raise awareness amongst consumers. In this sense, the role of actors and institutions capable of designing policies that value and stimulate the positive externalities of crop diversification with agroforestry and/or organic managements while taking into consideration the negative externalities of food production, which are usually excluded from the usual monetary profitability indicators, is absolutely crucial.

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CRediT authorship contribution statement

David Pérez-Neira: Conceptualization, Formal analysis, Methodology, Project administration, Visualization, Writing – review & editing. **Monika Schneider:** Investigation, Funding acquisition. **Laura Esche:** Formal analysis. **Laura Armengot:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Supplementary materials

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References

Aguilera, E., Díaz-Gaona, C., García-Laureano, R., Reyes-Palomo, C., Guzmán, G., Ortolani, L., Sánchez-Rodríguez, M., Rodríguez-Estévez, V., 2020. Agroecology for adaptation to climate change and resource depletion in the Mediterranean region. A review. Agrict. Syst. 181, 102809.

Aleksandrowicz, L., Green, R., Joy, E.J., Smith, P., Haines, A., 2016. The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: a systematic review. PLoS ONE 11 (11).

Altieri, M.A., Funes Monzote, F., Petersen, P., 2011. Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. Agron. Sustain. Develop. 32, 1–13.

Arizpe, N., Giampietro, M., Ramos-Martin, J., 2015. Food security and fossil fuel dependence: an international comparison of the use of fossil energy in agriculture (1991–2003). CRC Crit. Rev. Plant Sci. 30, 45–63.

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. Develop. 36, 70.

Armengot, L., Beltrán-Muñoz, M.J., Schneider, M., Simón, X., Pérez-Neira, D, 2021. Food-energy-water nexus of different cacao production systems from an LCA approach. J. Clean. Prod. 304, 126941.

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.

Bardi, U., El Asmar, T., Lavacci, A., 2013. Turning electricity into food: the role of renewable energy in the future of agriculture. J. Clean. Prod. 53, 224–231.

Bates, D., Machler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed effects models using lme4. J. Stat. Softw. 67, 1–48. https://doi.org/10.18637/jss.v067.i01.

Batlle-Bayer, L., Bala, A., Aldaco, R., Vidal-Mones, B., Colom, R., Fullana-i-Palmer, P., 2021. An explorative assessment of environmental and nutritional benefits of introducing low-carbon meals to Barcelona schools. Sci. Total Environ. 756.

Batlle-Bayer, L., Bala, A., Albertí, J., Xifré, R., Aldaco, R., Fullana-i-Palmer, P., 2020. Food affordability and nutritional values within the functional unit of a food LCA. An application on regional diets in Spain. Resour. Conserv. Recycl. 160, 104856.

Bayliss-Smith, T.P. (1982). The ecology of agricultural systems. Cambridge Topics in Geography: Second series, New York.

Bergendahl, J., Sarkis, J., Timko, M.T., 2018. Transdisciplinarity and the food energy and water nexus: ecological modernization and supply chain sustainability perspectives. Resour. Conserv. Recycl. 133, 309–319.

Bezner-Kerr, R., Madsen, S., Stüber, M., Liebert, J., Enloe, S., Borghino, N., Parros, P., Mutyambai, D.M., Prudhon, M., Wezel, A., 2021. Can agroecology improve food security and nutrition? A review. Glob. Food Security 29, 100540.

Caicedo, C., Pérez-Neira, D., Abad-González, J., Gallar, D., 2022. Assessment of the environmental impact and economic performance of cacao agroforestry systems in the Ecuadorian Amazon region: an LCA approach. Sci. Total Environ. 849 (25), 157795 https://doi.org/10.1016/j.scitotenv.2022.157795.

Cassidy, E.S., West, P.C., Gerber, J.S., Foley, J.A., 2013. Redefining agricultural yields: from tonnes to people nourished per hectare. Environ. Res. Lett. 8 (3).

Cerda, R., Deheuvels, O., Calvache, D., Niehaus, L., Sáenz, Y., Kent, J., Vílchez, S., Villota, A., Martinez, C., Somarriba, E., 2014. Contribution of cocoa agroforestry systems to family income and domestic consumption: looking toward intensification. Agroforestry Syst. 88, 957–981. https://doi.org/10.1007/s10457-014-9691-8.

Clapp, J., Moseley, W.G., Burlingame, B., Termine, P., 2021. The case for a six-dimensional food security framework. Food Policy, 102164.

Coulibaly, J.Y., Chiputwa, B., Nakelse, T., Kundhlande, G., 2017. Adoption of agroforestry and the impact on household food security among farmers in Malawi. Agric. Syst. 115, 52–69.

DeFries, R., Fanzo, J., Remans, R., Palm, C., Wood, S., Anderman, T.L., 2015. Metrics for land-scarce agriculture. Science 349, 6245.

Drewnowski, A., 2009. Defining nutrient density: development and validation of the nutrient rich food index. J. Am. Coll. Nutr. 28 (4), 421S.

Duffy, C., Toth, G.G., Hagan, R.P.O., et al., 2021. Agroforestry contributions to smallholder farmer food security in Indonesia. Agroforestry Syst. 95, 1109–1124.

Fajar-Putra, M.P.I., Pradhan, P., Kropp, J.P., 2020. A systematic analysis of water–energy–food security nexus: a South Asian case study. Sci. Total Environ. 728, 138451.

FAO, 2006. Food security. Policy brief. Food and Agriculture Organization (FAO) pb_issue2_final.indd (fao.org) (access: 12/12/2021).

FAO (2022): FAOSTAT. Online: https://www.fao.org/faostat/en/#data/QCL (access: 28/06/2022).

Filho, A.F., Fonseca, J.J., Jiménez, R., Ribeiro, A., Castro, E., 2014. Energy balance in the production of mountain coffee. Renew. Sustain. Energy Rev. 39, 1208–1213.

Fischer-Kowalski, M., Haberl, H., 2014. Socioecological Transitions and Global change: Trajectories of Social Metabolism and Land Use. Institute of Social Ecology, Klagenfurt University, Vienna, Austria. Edward Elgar Publishing, p. 288.

Ferguson, B.G., Aldasoro-Maya, M., Giraldo, O., Mier, M., Giménez-Cacho, T., Morales, H., Rosset, P., 2019. Special issue editorial: what do we mean by agroecological scaling? Agroecol. Sustain. Food Syst. 43 (7–8), 722–723.

Fluck, R., 1992. Energy of human labor. Energy in World agriculture. Energy in Farm Production. Elselvier.

Foley, DeFries, Jonathan A., Ruth, Asner, Barford, Gregory P., Carol, Bonan, Gordon, Carpenter, Chapin, Stephen R., Stuart Coe, F., Daily, Michael T., Gibbs, Gretchen C., Helkowski, Holly K., Holloway, Joseph H., Tracey, Howard, Kucharik, Erica A., Monfreda, Christopher J., Chad, Patz, Prentice, Jonathan A., Prentice, I., Ramankutty, Colin, Snyder, Navin, Peter, K., 2005. Global consequences of land use. Science 309, 570–574. https://doi.org/10.1126/science.1111772.

Gama-Rodrigues, A.C., Müller, M.W., Gama-Rodrigues, M.F., Teixeira Mendes, A., 2021. Cacao-based agroforestry systems in the Atlantic Forest and Amazon Biomes: an ecoregional analysis of land use. Agric. Syst. 194, 103270.

Giampietro, M., Bukkens, S.G.F., Pimentel, D., 1999. General trends of technological changes in agriculture. CRC Crit. Rev. Plant Sci. 18, 261–282.

Giampietro, M., Mayumi, K., 2000. Multiple-scale integrated assessment of societal metabolism: integrating biophysical and economic representations across scales. Popul. Environ. 22, 155–210.

Gockowski, J., Afari-Sefa, V., Sarpong, D.B., Osei-Asare, Y.B., Agyeman, N.F., 2013. Improving the productivity and income of Ghanaian cocoa farmers while maintaining environmental services: what role for certification? Int. J. Agric. Sustain. 11, 331–346.

González-García, S., Esteve-Llorens, X., Moreira, M.T., Feijoo, G.F., 2018. Carbon footprint and nutritional quality of different human dietary choices. Sci. Total Environ. 644, 77–94.

Green, A., Nemecek, T., Chaudhary, A., Mathys, A., 2020. Assessing nutritional, health, and environmental sustainability dimensions of agri-food production. Glob. Food Sec. 26, 100406.

Hirst, E., 1973. Energy Use For Food in the United States. Oak Ridge National Laboratory, Oak Ridge, Tennessee. ORNL-NSF-EP-57.

Hossain, M., Mullally, C., Asadullah, M.N., 2019. Alternatives to calorie-based indicators of food security: an application of machine learning methods. Food Policy 84, 77–91.

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. Sustain. Food Syst. 39, 798–823.

Jacobi, J., Mukhovi, S., Llanque, A., Augstburger, H., Käser, F., Pozo, C., Peter, M.N., Delgado, J.M.F., Kiteme, B.P., Rist, S., Speranza, C.I., 2018. Operationalizing food system resilience: an indicator-based assessment in agroindustrial, smallholder farming, and agroecological contexts in Bolivia and Kenya. Land Use Policy 79, 433–446.

Jiambo, L., 2006. Energy balance and economic benefits of two agroforestry systems in northern and southern China. Agric. Ecosyst. Environ. 116, 255–262.

Kuznetsova, A., Brockhoff, P.B., and Bojesen Christensen, R. B. (2015). lmerTest: tests in linear mixed effects models. R package version 2.0–29. http://cran.r-project.org/package=lmerTest (access: 07/03/2015).

Ponisio, L.C., M'Gonigle, L.K., Mace, K.C., Polomio, J., de Valpine, P., Kreme, C, 2015. Diversification practices reduce organic to conventional yield gap. Proce. Royal Soc. B – Biol. Sci. 282.

Leach, G., 1976. Energy and Food Production. IPC Science and Technology Press, London.

Lo, Y.T., Chang, Y.H., Lee, M.S., Wahlqvist, M.L., 2012. Dietary diversity and food expenditure as indicators of food security in older Taiwanese. Appetite 58 (1), 180–187.

Martínez-Blanco, J., Antón, A., Rieradevall, J., Castellari, M., Muñoz, P., 2011. Comparing nutritional value and yield as functional units in the environmental assessment of horticultural production with organic or mineral fertilization: the case of Mediterranean cauliflower production. Int. J. Life Cycle Assess. 16, 12–26.

Mahlknecht, J., González-Bravo, R., Loge, F.J., 2020. Water–energy–food security: a nexus perspective of the current situation in Latin America and the Caribbean. Energy 194, 16824.

Marco, I., Padró, M., Tello, E., 2020. Labour, nature, and exploitation: social metabolism and inequality in a farming community in mid-19th century Catalonia. J. Agrarian Change 20, 408–436.

McAuliffe, G., Takahashi, T., Lee, M.R.F., 2019. Applications of nutritional functional units in commodity-level life cycle assessment (LCA) of agri-food systems. Int. J. Life Cycle Assess. 25, 208–221.

Meemken, E.M., 2021. Do smallholder farmers benefit from sustainability standards? A systematic review and meta-analysis. Glob. Food Sec. 26, 100373.

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.

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. Engenharia Agrícola 35, 397–405.

Munisamy-Gopinath, D.P., 2021. Exploring the disparity in global food security indicators. Glob. Food Sec. 29, 100549.

Muller, A., Schader, C., et al., 2017. Strategies for feeding the world more sustainably with organic agriculture. Nat. Commun. 8 (1), 1290.

Murray, J., King, D, 2012. Climate policy: oil's tipping point has passed. Nature 481, 433–435.

Nag, P.K., Gite, L.P., 2020. Human-centered agriculture. Ergonomics and Human Factors Applied. Springer Nature, Singapore Pte. Ltd.

Niether, W., Jacobi, J., Blaser, W., Andres, C., Armengot, L, 2020. Cocoa agroforestry systems versus monocultures: a multi-dimensional meta-analysis. Environ. Res. Lett. 15 (10), 104085.

Nelson, G., Bogard, J., Lividini, K., Arsenault, J., Riley, M., Sulser, T.B., Mason-D'Croz, D., Power, B., Gustafson, D., Herrero, M., Wiebe, K., Cooper, K., Remans, R., Rosegrant, M., 2018. Income growth and climate change effects on global nutrition security to mid-century. Nat. Sustain. 1, 773–781.

Nkiaka, E., Okpara, U.T., and Okumah, M. (2021). Food–energy–water security in sub-Saharan Africa: quantitative and spatial assessments using an indicator-based approach. Environ. Develop.: 100655.

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 (2), 399–409.

Padró, R., Marco, I., Font, C., Tello, E., 2019. Beyond Chayanov: a sustainable agroecological farm reproductive analysis of peasant domestic units and rural communities (Sentmenat; Catalonia, 1860). Ecol. Economics 160, 227–239.

Pfeiffer, D.A., 2006. Eating Fossil fuels: Oil, Food and the Coming Crisis in Agriculture. New Society Publishers.

Pérez-Neira, D., 2016. Energy efficiency of cacao agroforestry under traditional and organic management. Agron. Sustain. Develop. 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.

Podolinsky, S., 2008. Human labour and unity of force. Historical Mater. 16, 163–183 (2008).

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360, 987–992.

Purwanto, A., Sušnik, J., Suryadi, F.X., de Fraiture, C., 2021. Quantitative simulation of the water–energy–food (WEF) security nexus in a local planning context in Indonesia. Sustain. Product. Consumpt. 25, 198–216.

R Core Team, 2015. R: A language and Environment For Statistical Computing. R Foundation for Statistical computing, Vienna, Austria. https://www.R-project.org/.

Ramírez, O., Somarriba, E., Ludewigs, T., Ferreira, P., 2001. Financial returns, stability and risk of cacao-plantation-agroforestry systems in Central America. Agroforestry Syst. 2, 141–154.

Recanati, F., Marveggio, M., Dotelli, G., 2018. From beans to bar: a life cycle assessment towards sustainable chocolate supply chain. Sci. Total Environ. 613–614, 1013–1023.

Röös, E., Bajzelj, B., Weil, C., Andersson, E., Bossio, D., Gordon, L.J., 2021. Moving beyond organic – A food system approach to assessing sustainable and resilient farming. Glob. Food Sec. 28, 100487.

Skaf, L., Buonocore, E., Dumontet, S., Capone, R., Franzese, P.P., 2021. Integrating environmental and socio-economic indicators to explore the sustainability of food patterns and food security in Lebanon. Curr. Res. Environ. Sustain. 3, 100047.

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

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

Smith, L., Kirk, D.J.D., Jones, P.J., Williams, A.G., 2019. The greenhouse gas impacts of converting food production in England and Wales to organic methods. Nat. Commun. 10, 4641.

Sonesson, U., David, J., Flysjö, A., Gustavsson, J., Witthöft, C., 2017. Protein quality as functional unit – a methodological framework for inclusion in life cycle assessment of food. J. Clean. Prod. 14, 470–478.

Taghizadeh-Hesary, F., Rasoulinezhad, E., Yoshino, N, 2019. Energy and food security: linkages through price volatility. Energy Policy 128, 796–806.

Vaitla, B., Coates, J., Glaeser, L., Hillbruner, C., Biswal, P., Maxwell, D, 2017. The measurement of household food security: correlation and latent variable analysis of alternative indicators in a large multi-country dataset. Food Policy 68, 193–205.

Wainaina, P., Minang, P.A., Duguma, L., Muthee, K., 2021. A review of the trade-offs across different cocoa production systems in Ghana. Sustainability 13, 10945.

Waldron, A., Garrity, D., Malhi, Y., Girardin, C., Miller, D.C., Seddon, N. (2017). Agroforestry can enhance food security while meeting other sustainable development goals. Trop. Conserv. Sci., January 2017.

Weindl, I., Ost, M., Wiedmer, P., Schreiner, M., Neugart, S., Klopsch, R., Kühnhold, H., Kloas, H., Henkel, I.M., Schlüter, O., Bußler, S., Bellingrath-Kimura, S.D., Ma, H., Grune, T., Rolinski, S., Klaus, S, 2020. Sustainable food protein supply reconciling human and ecosystem health: a Leibniz position. Glob. Food Sec. 25, 100367.

Yao, Y., Martínez-Hernández, E., Yang, A., 2018. Modelling nutrient flows in a simplified local food-energy-water system. Resour. Conserv. Recycl. 133, 343–353.