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Reducing fossil fuel dependency in smallholding farming in l'Horta de València, Spain: A socio-metabolic approach

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ABSTRACT

To favor transition towards sustainable agricultural systems, the agricultural sector needs to reduce its dependence on external inputs. From an ecological economics perspective, this requires the simultaneous fulfillment of a gross energy surplus on the farm (production condition), and a greater recirculation of the production extracted from the agroecosystem (reproduction condition). Using eight smallholder farms, this study focuses on the processes of recirculation and externalization of biomass, materials and energy flows in the agroecosystem. This is carried out through analyzing the MEFA (Material and Energy Flow Analysis) matrix by means of energy return on the investment indexes of inputs or externalizations (EFEROI), recirculations (IFEROI), joint efficiency (NPPact EROI) and labour efficiency (W EROI), all of which impact upon farm-scale decision-making related to yield and cost-benefit situations. Agrarian fossilization indices are applied to include an assessment of farm non-renewable energy profiles. The results indicate a restriction of inputs in conventional farm-operators and a troubling use of indirect fossil-fuel in organic operators, together with a weakening of the agroecosystem reproductive processes by means of external inputs for both systems. To guide the agrarian transition, farming strategies need to focus on reducing indirect fossil-fuel energy consumption, rather than relying on technological substitutions.

1. Introduction

In the current world-wide context of an agricultural price crisis and oil volatility, the strong fossil-fuel dependency and inefficiency of european agroecosystems threatens food production (Umar et al., 2021; McGreevy et al., 2022; Pinsard and Accatino, 2023). One of the main factors driving agrarian unsustainability is energy inefficiency, particularly assessed in conventional farming (Alonso and Guzmán, 2010; Ho, 2013; Guzmán et al., 2018). In order to tackle this unsustainable pathway in agrarian sector, organic farming is now in the spotlight of European Union agrarian and environmental policies (European Commission, 2020), as well as represents the horizon of several instruments regarding agrarian transition policy (European Commission, 2020b; European Commission, 2022). However, there is no common ground for addressing energy-related inefficiencies in organic models or practices, unlike for the conventional farming sector (Ramos-García et al., 2022; Navarro-Miró et al., 2022).

Several studies have compared economic, environmental impact or agrarian productivity performance in both production management models (Alonso and Guzmán, 2010; Ponisio et al., 2015; Stylianou et al., 2020; González-Molina et al., 2020; Su et al., 2021; Wang et al., 2022) however very few have quantified the practices driving un/sustainability at a farm-plot scale (Schleich et al., 2019), whether or not case-study farms are considered as organic or, reversely, as conventional. The analysis of energy and material exchanges at the plot or farm scale within a comprehensive agroecosystem's sustainability analysis is still an emerging field of research (Guzmán-Casado and González-Molina, 2017; Stylianou et al., 2020; Mazis et al., 2021), resulting in a dearth of literature comparing the efficiency of different agricultural production systems under umbrella terms such as 'organic' (Ramos-García et al., 2022) or 'conventional'. Since the decision-making process to allocate inputs and recirculation flows within the agroecosystems relies to a large extent on individual farmers, assessing their farm management and performance could provide specific information to orient public policies on agrarian sustainability.

Current conventional farms import large volumes of materials and energy from outside the system to guarantee their reproduction, often through the use of chemical fertilizers- (Aguilera et al., 2020; González-

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Molina et al., 2020; Wang et al., 2022), hence turning agroecosystems into net energy consumers (Tello et al., 2016b). This is mainly due to the substitution of natural and human capital through increased machinery use and pest management external inputs, resulting in a growing fossil fuel use (Fischer-Kowalski and Hüttler, 1998), as evidenced by numerous state-wide agricultural metabolism studies (Alonso and Guzmán, 2010; Aguilera et al., 2015; González-Molina et al., 2020; Wang et al., 2022).

Farming matter-energy-money decisions can be conceptualized as the different metabolic strategies used by farmers to both produce within and reproduce the agroecosystem (Marco et al., 2019; González-Molina et al., 2020) while continuing to ensure work and economic return (Tello et al., 2015). To explore metabolic pattern and performance, the analysis of matter, energy and information flows within agroecosystems becomes, according to Tello and Galán del Castillo (2013), a useful tool to identify strategic possibilities for the improvement of productivity efficiency. Acoording to Harchaoui and Chatzimpiros (2018) a key indicator is the Energy Return on Investment (EROI). Moreover, extended EROI rates (Tello et al., 2016b; Guzmán-Casado and González-Molina, 2017) provide detailed information upon sustainable energy management in agroecosystems. The input application strategies are the non-physical or management variable of the agroecosystem, constituted by practices, rights and authority (Marco and Tello, 2019; Marco et al., 2019) and are subsequently driven by innovation regimes and viable alternatives (Bui et al., 2016; Schilling et al., 2018; López-García et al., 2021).

The objective of the present study is to evaluate the extent to which direct and indirect fossil fuel dependency influences the energy efficiency of conventional and organic farms represented in l'Horta de València: a traditional agrarian region. We also examine how practices, economic performance and energy efficiency are related to sustainable management strategies pursued at farm scale. Overall, we seek to holistically address the current challenges related to the conditions of production and reproduction within local agri-food systems at farm-operator scale. By doing so in a comprehensive manner, we show how this helps in supporting decision-making processes aimed at increasing recirculation flows, reduces outsourcing flows and improves the yields of material, energy, income and work at farm scale. On-farm data were collected and inventoried to cover the statistic gap on consumption, production, flows and efficiency at farm scale in l'Horta de València (Spain) agroecosystems. We present a novel MEFA matrix, based on previous studies in the field of social metabolism (Tello et al., 2015, 2016b; Gingrich et al., 2018; Marco and Tello, 2019; Marco et al., 2019), which innovatively allows for the simultaneous analysis of the efficiency of internal recirculation, externalization, economic gain and fossil dependency processes. This analytical approach provides information about potential public policy implications considering the current Green Deal European Framework and the Common Agrarian Policy (European Commission, 2020; European Commission, 2020b) as well as for ongoing approaches for agrarian transition in the area as referred by López-García et al. (2021).

2. Analytical approach

Our work is framed within the current field of studies focused on the use of energy efficiency indicators, historically underpinned by three foundational paradigms: (1) the bioeconomic fund-flow approach; (2) social metabolism; (3) integrated agrarian sustainability analysis. The bioeconomic fund-flow approach to the social appropriation of nature recognizes that all productive flows are sustained by reproductive flows (Marco and Tello, 2019; Marco et al., 2019), which in turn originate from either the natural fund, or ecosystems (Georgescu-Roegen, 1971). A traditional agrarian metabolism is an energy dissipating system supplying socioeconomic circuits (Guzmán-Casado and González-Molina, 2017). Agroecosystem productivity is appropriated through work (draft animal, human) and fed back through inputs, mainly derived from the productivity of livestock (Gingrich et al., 2018). Conventional practices (González-Molina et al., 2020) would only temporarily and locally replace these returns through 1) the use of machinery which substitutes human and workhorse work, and 2) inputs such as fertilizers, pest management external inputs and fuel replacing agroecosystem internal processes. A farm's financial capacity and the availability of fuel could be central to this replacement (Aguilera et al., 2020; Stylianou et al., 2020). In this manner, the recirculation of biomass and energy, typical of traditional agroecosystems performance, is substituted by a linear process of externalization of flows (González-Molina et al., 2020). However, recirculation is essential within agroecosystems in order to maintain their productivity (Ho and Ulanowicz, 2005). Furthermore, a broad consensus exists whereby agricultural sustainability strategies need to reduce dependence on external inputs (Tripp, 2005; Fess and Benedito, 2018; Stylianou et al., 2020), particularly fertilizers (Li et al., 2017; Harchaoui and Chatzimpiros, 2018; González-Molina et al., 2020).

In order to identify "sustainable" agricultural management, benchmarking between different agricultural management systems at a wide regional scale has been recently studied by Su et al. (2021) and Wang et al. (2022). Integrated sustainability analyses have increased in recent years (Janker and Mann, 2018; Stylianou et al., 2020; Marull et al., 2021; Ripa et al., 2021; Borychovski et al., 2020). Other studies (Alonso and Guzmán, 2010) and meta-studies (Fess and Benedito, 2018; Aguilera et al., 2020) have also evaluated the efficiency in the use of Non-Renewable Energies (NRE) in both organic and conventional agriculture at the state or regional level, by means of using energy efficiency indicators (multi-EROI assessment). Results provided by Alonso and Guzmán (2010), Suja et al. (2017) and Fess and Benedito (2018) and found greater NRE efficiency in organic farming, albeit with a lower yield, than when compared to conventional farming. Case-studies have been carried out to balance energy efficiency within agrarian models, such as those carried out for diversified farming systems (Schleich et al., 2019) or organic cattle systems (Ramos-García et al., 2022).

The substitution of flows and the low efficiency in its management by means of fossil fuel inputs are both characteristic of conventional agricultural systems (Aguilera et al., 2015; Harchaoui and Chatzimpiros, 2018; González-Molina et al., 2020). Conversely, pre-industrial or traditional agriculture relies on the recycling of energy and materials within the agroecosystem, showing greater efficiency in the use of flows (Tello et al., 2016a; Guzmán-Casado and González-Molina, 2017; Fullana-Llinàs et al., 2021). Organic agriculture also aims at recycling energy and material within the agroecosystem. The range of alternative management strategies within organic and conventional agriculture, and the scope in the substitutability of external inputs by recirculation have been conceptualized as LEIT (Low External Input Technologies) and LME (Law of Minimum EROI) strategies (Tripp, 2005; Tello et al., 2016b).

Sustainable smallhold farming transitions in the study area of l'Horta de València have been recently examined by López-García et al. (2021), particularly those of conventional farmers. According to this research, the current agrarian sector in the area suffers from several problems such as profitability and growing operational costs, leading wether to agricultural abandonment, intensification or shifting agrarian practices implementation, historically represented by crop replacement (Hermosilla-Plá and Membrado-Tena, 2018; López-García et al., 2021; Melo, 2020). The energy efficiency assessment method helps broaden the analysis over agroecosystems management, as stated by Guzmán-Casado and González-Molina (2017). Combining sets of EROI allows a simultaneous assessment of the differing agroecosystems traits such as flow patterns, decision-making of inputs allocation, fossil dependence and the farmer's aim to reproduce their live funds sustainably, as stated by Fullana-Llinàs et al. (2021) stated. As far as the authors are aware of, no real discussion has been generated regarding organic energy performance and range nuances within agrarian models in the area from an energy efficiency and fossil fuel inputs perspective, nor have strategies

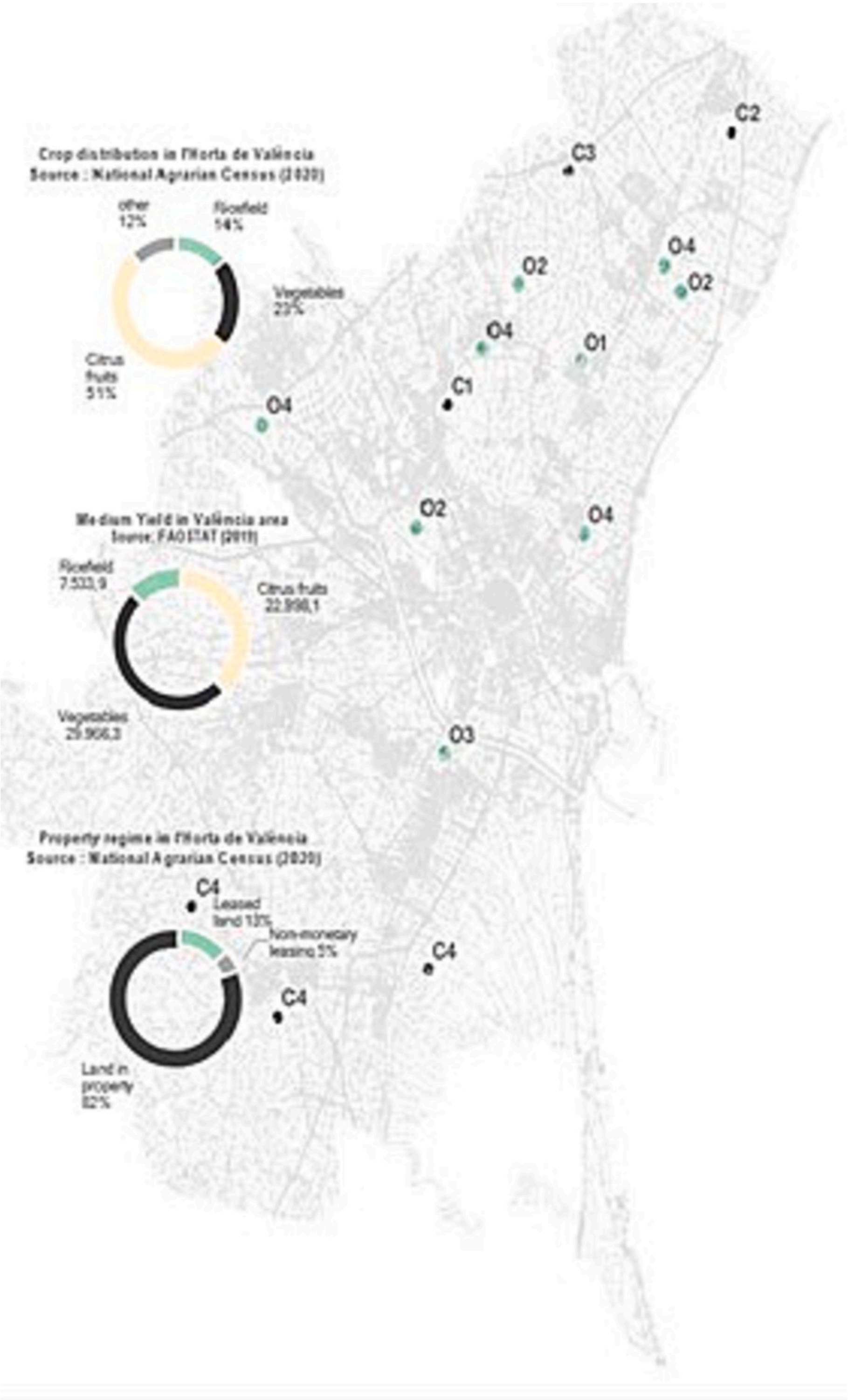


Fig. 1. Sample distribution in l'Horta de València (1:225000). Crop distribution (ha), property regime (ha) and medium yield (kg ha^{-1}). Source: our own with data released in National Agrarian Census (CADRECTE, 2021) and Food and Agriculture Organization (2020). O1 to C4 acronyms refer to sample coding.

Table 1

Sample short-list for the case study of l’Horta de València. Source: our own elaboration, based on the data obtained from interview, field visit and farm book consultation for the 2020 agricultural season. See supplementary materials for further information on data gathering.

Smallhold farmer code	Total crop hectares	Total annual yield per hectare	Commercial crops	Rotation practice	Fallow practice	Workload per year	Machinery use	Mechanization degree	Fertilization practice	Total fertilizer	Pest management	Weed management	Access to subsidies	Commercial yield per hectare	Total operational costs
O = organic C = conventional	Hectares (ha)	(kg dm year^{-1} ha^{-1})	Types per year	units	Units per year	h year^{-1}	h ha^{-1} year^{-1}	qualitative	type	(MJ year^{-1} ha^{-1})	type	type	€ year^{-1} ha^{-1}	€ year^{-1} ha^{-1}	€ year^{-1} ha^{-1}
O1	0,41	7.018,40	Vegetable mix and citrus fruits	seasonal	One season per terrace	5.597,85	18	Light-duty machinery	Workhorse manure, green manure and mulching	30.883,5	Integrated	Manual removal	0,00	22.439,02	7.634,20
O2	2,17	1.815,00	Vegetable mix	seasonal	One season per terrace	3.315,24	7,28	Heavy machinery	Sheep manure and mulching	99.933,7	Microbian, Paraffin oil and cupper	Mechanical removal	0,00	70.967,74	30.053,38
O3	5,00	8.325,00	Vegetable mix and tuber	seasonal	Between tuber seasons	6.723,67	48,9	Light-duty and heavy machinery	Chicken manure and mulching	52.727,0	Microbian, cupper and sulfur	Mechanical removal	875,00	25.562,40	18.873,18
O4	28,00	2.807,80	Vegetable mix and tigernut	seasonal	Between tigernut seasons	3.714,90	16,06	Heavy machinery	Chicken manure and mulching	88.830,0	Microbian, cupper and sulfur	Mechanical removal	27,68	59.733,04	22.736,98
C1	1,00	18.600,00	Citrus fruits and tuber	seasonal	Between tuber seasons	936,00	21,26	Light-duty and heavy machinery	Prunning and trimming inc., clover manure, chicken manure	46.816,0	Insecticide and cupper	Mechanical removal	0,00	2.100,00	2.455,45
C2	1,96	1.704,86	Citrus fruits	none	none	368,56	23,44	Light-duty and heavy machinery	Synthetic NPK	40.128,0	Insecticide, cupper and sulfur	Herbicide	1.000,00	1.981,38	1.674,71
C3	1,38	7.797,43	Traditional triad and citrus	seasonal	none	1.031,07	31,06	Light-duty and heavy machinery	Chicken manure, mulching	58.354,0	Insecticide, cupper and sulfur	Herbicide	0,00	39.472,17	8.346,09
C4	14,5	558,68	Cardoon and rice	none	none	417,10	20,98	Heavy machinery	Synthetic NPK	60.192,0	Insecticide, cupper and sulfur	Herbicide	1.034,48	5.300,00	2.509,86

been pursued to balance energy and economic profiles of local agroecosystems in l’Horta de València.

3. Methods

We developed a case study approach (Section 3.1) (see supplementary materials for extended data gathering). A MEFA matrix was constructed (Section 3.2.1) to evaluate snap-shot agrometabolic performance by means of a productive and reproductive accounting balance. A set of Energy Return Rates (EFEROI, IFEROI, NPP_{act} EROI, W EROI) and two indices of agrarian fossilization (F1,F2) (Section 3.2) were applied to a sample of eight smallholder farms selected within l’Horta de València area over the 2020 agricultural season.

3.1. Case study: l’Horta de València

l’Horta de València is a historical agricultural and peri-urban territory of the city of Valencia comprising 19,502 (ha) of horticultural and woody crops (see Fig. 1). Irrigation farmland represents 93% of the surface area. Average farm size is 3.7 ha according to National Agrarian Census (2020). Intensive or conventional agriculture represents the majority of the smallholdings, characterized by 1 to 3 annual rotations (vegetables crop areas) or 1 harvest per year (rice or citrus crop areas). Traditional polyculture for l’Horta de València farmers are pumpkin-beans-artichoke and potato-onion-tigernut, with a crop replacement trend (citrus fruits) during past century, though now in decline (Hermosilla-Plá and Membrado-Tena, 2018). The vegetable polyculture has been indeed progressively replaced by ‘machinable’ crops like potato, onion, tigernut and pumpkin (López-García et al., 2021).

Purposive sampling is applied to obtain contrasting data within study area. Four organic (O) and four conventional (C) farmers ($N = 8$) were selected (see Fig. 1 for the sample distribution and Table 1 for a detailed description). Representativeness criteria is based on agricultural diversity in area, depart from model (conventional, organic certified and organic non certified), crop orientation (rice, orange, vegetable mix, tuber, tigernut), farmer workload (full-time, part-time) and degree of mechanization (light-duty machinery and workhorse or heavy machinery use). Together, the selected farmers owned 48,4 ha, of which 45% was under organic certification, 16% organic non-certified and 38% under conventional cultivation. Crop orientation, farmer workload and degree of mechanization diversity are as well represented in the sample for the study area (see Table 1).

3.2. Methods of energy accounting at farm scale

3.2.1. Snap-shot agrometabolic model and MEFA matrix: production and reproduction energy accounting balances

A snap-shot agrometabolic model (Fig. 2) was constructed based on Gingrich et al. (2018). Productive and reproductive dimensions of targeted agroecosystems were used to assess metabolic patterns. Following Guzmán-Casado and González-Molina (2017) we calculated actual Net Primary Production (NPP_{act}) by combining the unharvested biomass (NHB) from weeds and wild plants not removed in farmplots, and total harvested biomass (HB) of aerial and root fractions of yield and non-commercial yield (Y, Y_{nc}).

After having conducted a literature review on embodied energy (EE) (Guzmán and González-Molina, 2015; Aguilera et al., 2015; Gingrich et al., 2018; Mazis et al., 2021), total non-renewable energy (CE) accounts for every entry flow fraction with a fossil-fuel source (C0,C1,C2, C3): human feed outside the farmplot (C0), pest management external inputs, fertilizers fraction assignable to fossil fuel input and workhorse feed fraction from outside the farm (C1), the sum of embodied energy in machinery use, irrigation and refrigerated storage (C2) and direct fuel use in operation (C3).

In order to account for farmplot self-sufficiency in closing biomass and energy loops, we split recirculating sources into external (REB) and internal (RIB), as shown in Fig. 3. Total renewable energy from internal and recirculated flows (RIB) accounts for internal flow fractions such as human (Ffb) and workhorse feed (Fhb) inside the farmplot, non-harvested biomass and waste or green cover incorporation (Ync, W, NHB), workhorse manure (Hmb) and productive and reproductive or care work in the farmer’s family unit (Wp,Wr). Following (Marco and

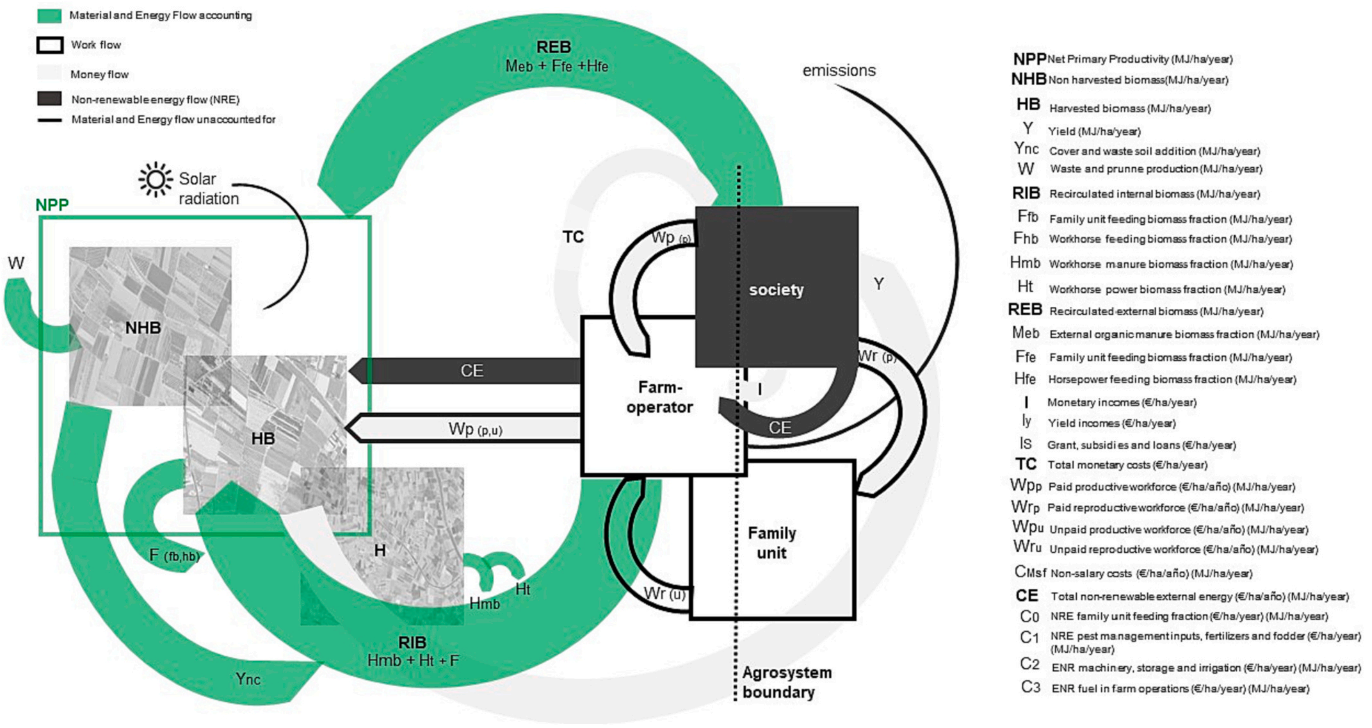


Fig. 2. Appropriation, recirculation and externalization basic scheme for agroecosystems. Source: our own based on Gingrich et al. (2018) and (Marco and Tello, 2019; Marco et al., 2019).

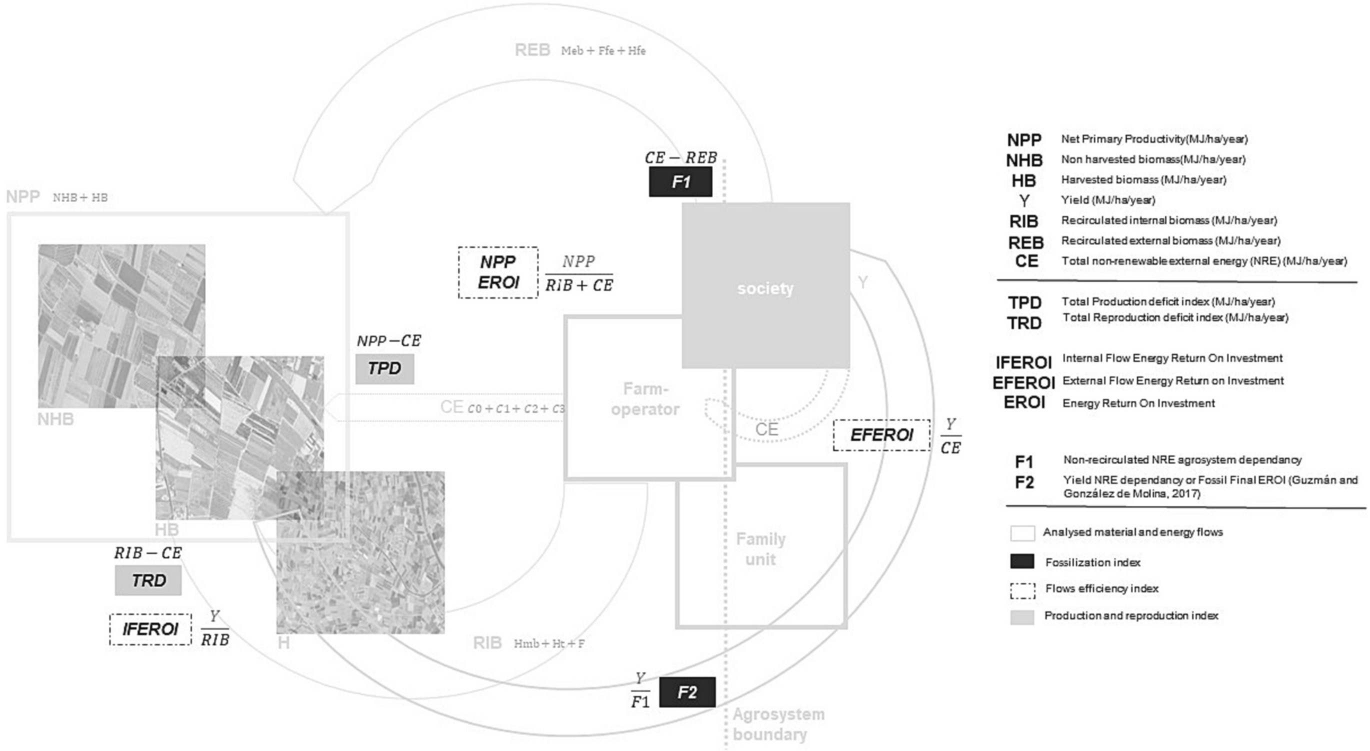


Fig. 3. Material and energy flow accounting matrix and assessment index for snap-shot agroecosystem MEFA matrix. Source: our own.

Tello, 2019; Marco et al., 2019) this approach aims to incorporate all necessary human workloadto sustain the agroecosystem, wether paid or unpaid. REB equals to fractions prorated from CE which can refer either to soil, work or draft incorporation of inputs (Meb,Ffe,Hfe) (see supplementary material for extended variable's calculation). The exit flows or domestic extraction of energy and materials suppose the transfer from the agroecosystem to society, implying harvested biomass (HB), non-incorporated residues (W) and pollutant emissions. We excluded pollutant emissions calculations (soil and water, exhaust emissions) in any form as they exceed the scope of the study.

The full material and energy flow and assessment indices (see Sections 3.2.2 and 3.2.3) are shown in Fig. 3. The MEFA metabolic matrix of the agroecosystem (Fig. 2) integrates the different processes needed for the analysis through the productive (TPB) and reproductive (TRB) balances described in Table 2.

Quantification of economic relations within and outwith the agroecosystem boundaries aims to assess farm management and input application strategies of the farmer. Thus, total annual costs (TC) were calculated as the summation of paid workforce (Wpp, Wrp) and non-salary direct and indirect depreciated costs of inputs (CMSf). Net revenues (G) were calculated as the summation of sale incomes (I_y), grants and subsidies (I_s) per year minus TC, taxes and annual loan repayment. Gross margin (GM) is calculated as referred in National Accountability Agrarian Network (Ministerio de Agricultura, Pesca y Alimentación, 2020), as this index provides comparability intra and extra sample. Following Fullana-Llinàs et al. (2021) we have conducted the calculation of 'EROI on Labour' index (see Table 3). We include the labour of farmers and paid workforce and also unpaid labour of and within family unit. Unpaid family labor still remains an important feature in the agrarian sector, reflecting traditional farming systems (Marco and Tello, 2019; Marco et al., 2019).

Table 2
Agroecosystems production and reproduction conditions. Source: our own.

Abbrev.	Balance	Units	Description
TPB	$TP-CE$	MJ ha^{-1} year^{-1}	Production condition: material and energy synthetic balance between net primary production and total NRE import to the agroecosystem
TRB	RIB– CE	MJ ha^{-1} year^{1}	Reproduction condition: material and energy synthetic balance between internal biomass recirculation and total NRE import to the agroecosystem

Table 3
MEFA matrix agroecosystem, energy, labour and economic efficiency index. Source: our own.

Abbreviation	Index	Units	Description	Source
EFEROI	$\frac{HB}{CE}$	Non-dimensional	External Input Final Return On Investment	Pimentel and Giampietro (1994)
IFEROI	$\frac{HB}{RIB}$	Non-dimensional	Internal Input Final Return On Investment	Tello et al. (2015, 2016b)
NPP$_{act}$ EROI	$\frac{NPP}{RIB+CE}$	Non-dimensional	Total final Input Return On Investment. Calculation procedure equals this formula to FEROI ratio (Tello et al., 2016a)	Guzmán-Casado and González-Molina (2017)
G	$I-TC$	€ ha^{-1} year^{-1}	Net revenues per hectare	–
GM	$\frac{I-TC}{I}$	Non-dimensional	Gross-margin of activity	Ministerio de Agricultura, Pesca y Alimentación (2020)
W EROI	$\frac{HB}{Wpnr+Wpr}$	Non-dimensional	Labour Energy Return on Investment	Fullana-Llinàs et al. (2021)

Table 4
Agroecosystem fossilization index applied to snap-shot agrarian MEFA matrix. Source: our own.

Abbreviation	Index	Units	Description
F1	$CE - REB$	MJ ha^{-1} $year^{-1}$	Agroecosystem flows non-recirculable fossil dependance
F2	$\frac{Y}{CE - REB}$	Non-dimensional	Yield fossil dependance or 'Fossil Final EROI' as defined in Guzmán and González-Molina (2015)

3.2.2. *Energy efficiency and socioeconomic return rates*

We analyzed the efficiency of energy, labour and economic processes within snap-shot MEFA matrix. Energy return ratios of external (EFEROI), internal (IFEROI) and actual-final-joint of total inputs (NPP_{act} EROI) are included following multi-EROI approaches (see Table 3). Labour EROI (W EROI) and two economic index (G,GM) are selected to assess socioeconomic performance.

3.2.3. *Agrarian fossilization indices*

We included two indicators of fossilization: fossil deficit in the agroecosystem (F1) and yield dependance on fossil fuels (F2) (see Table 4), called Fossil Final EROI (Guzmán-Casado and González-Molina, 2017). These indicators assess the degree of non-renewable dependence, coined 'fossilization' by Carpintero and Naredo (2006). Index F1 provides an annual energy balance of fossil-fuel energy use non directly recirculated within the agroecosystem, as its calculation detracts all external flows with direct contribution to agroecosystem's socionatural funds (A_{eo} organic manure embeddable fraction, F_{fe} family feeding biomass fraction and H_{fe} draft animal feeding biomass fraction). This index therefore pertains to an agroecosystem's fossil dependance on external flows, shown as deficit balance. Index F2 or Fossil Final EROI rates the efficiency of these flows over the total annual yield (Y). Together they demonstrate the balance (F1) and the energy return (F2) within the agroecosystem with respect to both NRE and non-recirculated material and energy flows.

3.3. *Data sources*

Process indicators and energy balances of farms were then estimated. An estimation of the Embodied Energy (EE) of machinery and supplies was carried out using a conservative criterion. Here we considered depreciation energy costs derived from production, together with energy costs of the operating fuel and human workload, based on data from previous studies by Aguilera et al. (2015), Mazis et al. (2021) and Stylianou et al. (2020). Using annual work units (AWU),we then calculated fuel consumption for machinery operations based on the IDAE report Instituto para la Diversificación y el Ahorro Energético (IDAE) (2005). Data regarding energy unit per crop, energy unit per unharvested biomass, dry matter conversion for fresh harvest, green fodder energy content and waste production per crop were based on the work from Guzmán and González-Molina (2015) (see supplementary materials for extended conversion and biomass partitioning tools). Irrigation water (by gravity in all cases, excepting certain plots within the O4 farm -drip irrigation-), was included in the energy balance. The values used for determining irrigation energy use were 1.27 kW ha-^{1} (Rodríguez-Díaz and Camacho, 2011) and 0.0056 MJ ha-^{1} (Aguilera et al., 2015) for drip and surface irrigation respectively. Biomass and economic data are derived from direct interviews with farmers, farm book consultation and field visits during t the agrarian season under research.

Table 5
Energy accounting balances in four organic (O) and conventional (C) l'Horta de València agroecosystems. Source: our own.

Energy accounting indicators and elements		Productive flows balance	Reproductive flows balance	Actual NPP	Commercial yield	Total harvested biomass	Total non-harvested biomass	Recirculated flows (internal and external)		Total non-renewable energy entry flows				
		MEFAp (TPB)	MEFAr (TRB)	Actual NPP (NHB + HB)	Y	HB	NHB	RIB	REB	0CE	1CE	2CE	3CE	CE
			MJ ha^{-1} $year^{-1}$											
organic	O1	103.853,65	10.104,59	155.848,93	16.219,39	155.797,85	51,08	165.953,51	48.884,89	6.221,61	44.118,90	403,21	1.251,56	51.995,27
	O2	−26.090,70	−9.572,75	101.313,05	22.619,03	101.293,89	19,15	91.740,30	111.161,84	11.228,09	99.933,75	7.276,79	8.965,11	127.403,75
	O3	49.641,98	−34.906,37	110.638,07	34.986,60	110.606,15	31,92	75.731,70	55.620,86	2.893,85	52.727,01	418,46	4.956,77	60.996,09
	O4	−13.307,70	5.477,68	92.716,15	21.185,64	92.703,38	12,77	98.193,83	91.855,67	3.025,67	88.830,00	5.622,26	8.545,92	106.023,84
conventional	C1	694,67	−14.553,02	55.471,16	3.414,02	55.369,01	102,16	40.918,14	2.769,50	2.769,50	46.816,00	152,48	5.038,51	54.776,49
	C2	−15.299,52	−2.995,20	34.074,01	3.206,85	34.067,63	6,38	31.078,81	2.631,02	2.631,02	40.128,00	1.140,13	5.474,38	49.373,53
	C3	21.007,78	−6.133,91	91.892,20	6.243,50	91.885,82	6,38	85.758,29	64.243,47	5.889,47	58.354,00	249,56	6.391,40	70.884,43
	C4	−50.109,41	−7.692,81	26.578,87	7.692,81	26.572,49	6,38	18.886,06	3.054,32	3.054,32	60.192,00	662,85	12.779,12	76.688,29

MEFAp = Material and Energy Flow Analysis of production flows; MEFAr = Material and Energy Flow Analysis of reproduction flows; NHB = Non-harvested biomass; HB = Harvested Biomass; Y = commercial yield; RIB = Recirculated internal Biomass flows; REB = Recirculated external Biomass flows; CE = Total Non-Renewable energy (NRE) entry flows; 0CE = NRE family unit feeding flow fraction; 1CE = pest management external inputs, fertilizer and fodder NRE entry flow fraction; 2CE = machinery, refrigerated storage and irrigation NRE entry flow fraction; 3CE = fuel in operation NRE entry flow fraction.

4. Results

4.1. Energy accounting balance indicators at farm scale

4.1.1. Farm-operator production and reproduction MEFA balances

Energy Accounting balances of snap-shot MEFA matrix are shown in Table 5. Within the study sample, a maximum agroecosystem actual Net Primary Productivity (NPPact) of 155,84 MJ ha^{-1} year^{-1} is reached for organic farmer O1 (citrus fruits and mixed vegetables, with several annual harvests), and a minimum of 26,578 MJ ha^{-1} year^{-1} is reached in C4 (rice and cardoon, one yield each per year).

The balance between the actual net Primary Productivity of the agroecosystem and external NRE entry flows practiced on the farm (operations, machinery, fertilizers and pest management external inputs, and imputable feed and fodder fraction) is negative for both O2 and O4, the largest organic operators in terms of production and farm-size (TPB$\overline{O2, O4}$ -19,699.20 MJ ha^{-1} year^{-1}). Conversely, in farms O1 and O3, such a balance is, conversely, positive, with an average surplus (TPB$\overline{O1, O3}$, 76,747.82 MJ ha^{-1} year^{-1}). Farms operating under conventional practices present an average productive deficit (TPB$\overline{c}$, −10,926.62 MJ ha^{-1} year^{-1}). Only citrus fruits under conventional farming with minimum-input practices (no tillage, no weed removal) show farm energy production surplus (TPB$\overline{C1, C3}$,10,851.23 MJ ha^{-1} year^{-1}).

The reproductive flows balance is positive for organic farmers O1 and O4 exclusively (TRB$\overline{O1, O4}$, 7.791,13 MJ ha^{-1} year^{-1}). Entry flows with fossil sources (0CE…3CE) are similar between conventional farmers, while higher differences are found in organic farms (1CE$_{O1}$ 11.180,90 MJ ha^{-1} year^{-1}; 1CE$_{O2}$ 99.933,75 MJ ha^{-1} year^{-1}) particularly in relation to the pest management external inputs, fertilizer and fodder category. Recirculated external flows (REB) range between the lowest annual value of 2.631,02 MJ ha^{-1} year^{-1} (C2) and the highest sample value with 111.161,84 MJ ha^{-1} year^{-1} (O2). Recirculated internal flows also differ between of organic and conventional, with the exception of C3 operator. The highest value corresponds to organic 165.953,51 MJ ha^{-1} year^{-1} (O1) and lowest to conventional (C4) 18.886,06 MJ ha^{-1} year^{-1}.

4.1.2. Energy efficiency in snap-shot MEFA matrix for agroecosystems in l'Horta de València

For the operators studied, energy efficiency rates of studied of the annual agroecosystem's metabolism are shown in Table 6. No trends are observed within organic or conventional operators in terms of energy efficiency of external inputs. Half of organic agroecosystems (O1,O3) show great efficiency, rating 3:1–2:1. Put simply, three units are produced for every one external input. Positive performance of the biomass and energy recirculation process, or internal inputs (IFEROI less than 1) is observed in half of the organic operators (O1,O4). Joint final efficiency of inputs (NPP$_{act}$ EROI) is less than 1 in the sample, although organic agroecosystems perform better than conventional ones (NPP$_{act}$ EROI$\overline{O1 \ldots O4}$ 0,61; NPP$_{act}$ EROI$\overline{C1 \ldots C4}$ 0,47).

Table 6

Agroecosystems inputs return on investment ratios (NPPact EROI, EFEROI, IFEROI) in four organic (O) and four conventional (C) farms in l'Horta de Valencia. Source: own elaboration.

Energy efficiency index	O1	O2	O3	O4	C1	C2	C3	C4
EFEROI	3,00	0,80	1,81	0,87	1,01	0,68	1,29	0,34
IFEROI	0,94	1,01	1,46	0,94	1,35	1,09	1,07	1,40
NPP$_{act}$ EROI	0,72	0,46	0,81	0,45	0,58	0,42	0,59	0,28

EFEROI = External Energy Return On Investment; IFEROI = Internal Energy Return On Investment, NPPact EROI = Actual Net Primary Productivity EROI.

4.1.3. Assessment of farm-operator socioeconomic flows in l'Horta de València agroecosystems

Results are shown in Table 7 (see Tables A.5 and A.6 in supplementary materials for detailed analysis). Organic model net revenues range between 11.064,2 € ha^{-1} year^{-1} and 40.914,3 € ha^{-1} year^{-1}. A deficit of −355,45 € ha^{-1} year^{-1} is found for a single conventional farmer (C1 – citrus fruits). Net revenue close to the maximum occurs in polyculture farms oriented to either several local channels (O2) or to national markets (C3). Gross margin performance is positive within the sample, excluding (C1). Labour EROI differs widely within the sample, ranging from 1,4 (C2 – citrus fruits) and 30,8 (O1 – vegetable mix and citrus fruits), followed by 20,9 (C3 – citrus fruits and traditional triad).

4.2. Fossil profiles and dependence assessment in l'Horta de València agroecosystems

Fig. 4 shows the sample fossil energy efficiency assessment in sample by means of total NRE entry minus recirculated fraction and final efficiency over agroecosystem commercial yield. Differences arise between agrarian management models: higher total harvest per hectare is found for those organic (HB$\overline{O1 \ldots O4}$ 115.100,3 MJ ha^{-1} year^{-1} compared to HB$\overline{C1 \ldots C4}$ 51.973,7 MJ ha^{-1} year^{-1}) along with lower non-recirculable NRE entry flows (F1$\overline{O1 \ldots O4}$ 9.723,9 MJ ha^{-1} year^{-1} compared to F1$\overline{C1 \ldots C4}$ 44.756,1 MJ ha^{-1} year^{-1}).

With respect to fossil final EROI (F2), three trends are found in sample. Half of the organic and one conventional farmers show a ratio close to 1:1 (O2,O4,C3), while the rest of the organic (O1,O3) perform close to 5:1 ratio for commercial yield and non-recirculated fossil-fuel input. The last trend is represented exclusively by conventional farmers (C1,C2,C4) with low commercial yield compared to non-recirculated fossil-fuel input.

Fossil-fuel input profiles, or 'externalization profiles' (Fig. 5), show total non-renewable energy cost (CE) by input. The median value of total non-renewable energy input in the sample for organic farms stands at 86.604,7 MJ ha^{-1} year^{-1}, compared to 62.930,6 MJ ha^{-1} year^{-1} in conventional farms. The fossil-fuel subset with the highest contribution in all cases is that of fertilizers ($\overline{O1 \ldots C4}$ 59.733,04 MJ ha^{-1} year^{-1}). Differences appear between agrarian management models ($\overline{O1 \ldots O4}$ 68.093,57 MJ ha^{-1} year^{-1} compared to $\overline{C1 \ldots C4}$ 51.372,50 MJ ha^{-1} year^{-1}). Per commercial yield unit, organic farmers allocate close to 2 energy units of fertilizer while those conventional range between 1:9 and 1:14.

Applied fertilizers (mineral, layer manure, horse manure, sheep and sheep pellets) for both organic and conventional farms account between 59 and 82% of CE respectively, with comparable distributions in weight for both types of farms. The cost in energy weight within the farm escalates sharply in the case of small farms, the traditional farm size within the analyzed territory being between 1 and 3 ha.

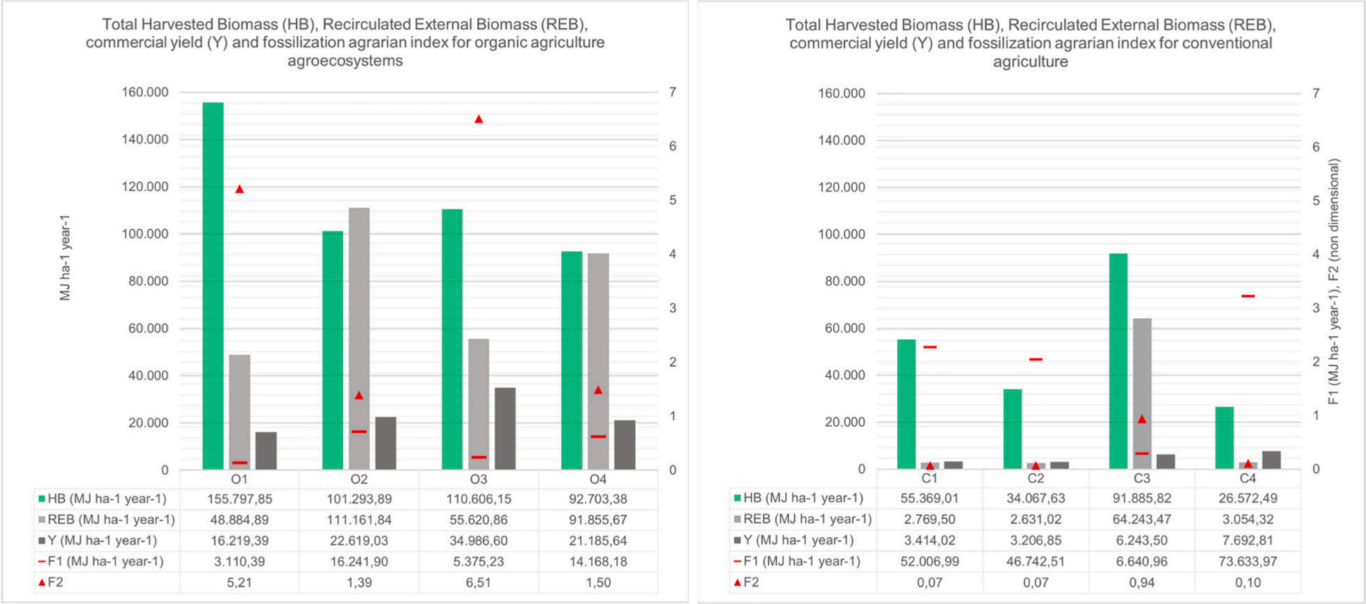
5. Discussion

5.1. Energy balance from farm-operator standpoint: an elephant in the room

External and non-renewable fossil fuel input and low recirculation profiles are a trait of both organic and conventional farming management practices within l'Horta de València agroecosystems. This finding is consistent with previous studies at broader scales (Alonso and Guzmán, 2010; Aguilera et al., 2015; González-Molina et al., 2020; Su et al., 2021) and within historical period comparisons between traditional agriculture and the industrial period (Fullana-Llinàs et al., 2021). The calculated TPB balance shows a deficit for half of both organic and conventional agroecosystems. Farms with low mechanization and intended non-harvested areas show surplus (O1,O3,C1,C3) when compared to the rest of the sample. Even so, conventional farming does

Table 7
Economic performance and agroecosystems labour inputs return on investment ratios (W EROI) in four organic (O) and four conventional (C) farms in l'Horta de Valencia. Source: own elaboration.

Index	Description	O1	O2	O3	O4	C1	C2	C3	C4
Net revenues	$I - TC$	14.804,8	40.914,3	11,064,2	14,738,8	−355,4	2.266,6	31.126,08	17.790,1
Gross margin	$\frac{I - TC}{I}$	65%	57%	36%	62%	0%	57%	78%	87%
W EROI	$\frac{HB}{Wpnr + Wpr}$	30,8	13,9	3,4	8,2	5,3	1,4	20,9	1,9



	O1	O2	O3	O4
🟩 HB (MJ ha-1 year-1)	155.797,85	101.293,89	110.606,15	92.703,38
■ REB (MJ ha-1 year-1)	48.884,89	111.161,84	55.620,86	91.855,67
■ Y (MJ ha-1 year-1)	16.219,39	22.619,03	34.986,60	21.185,64
− F1 (MJ ha-1 year-1)	3.110,39	16.241,90	5.375,23	14.168,18
▲ F2	5,21	1,39	6,51	1,50

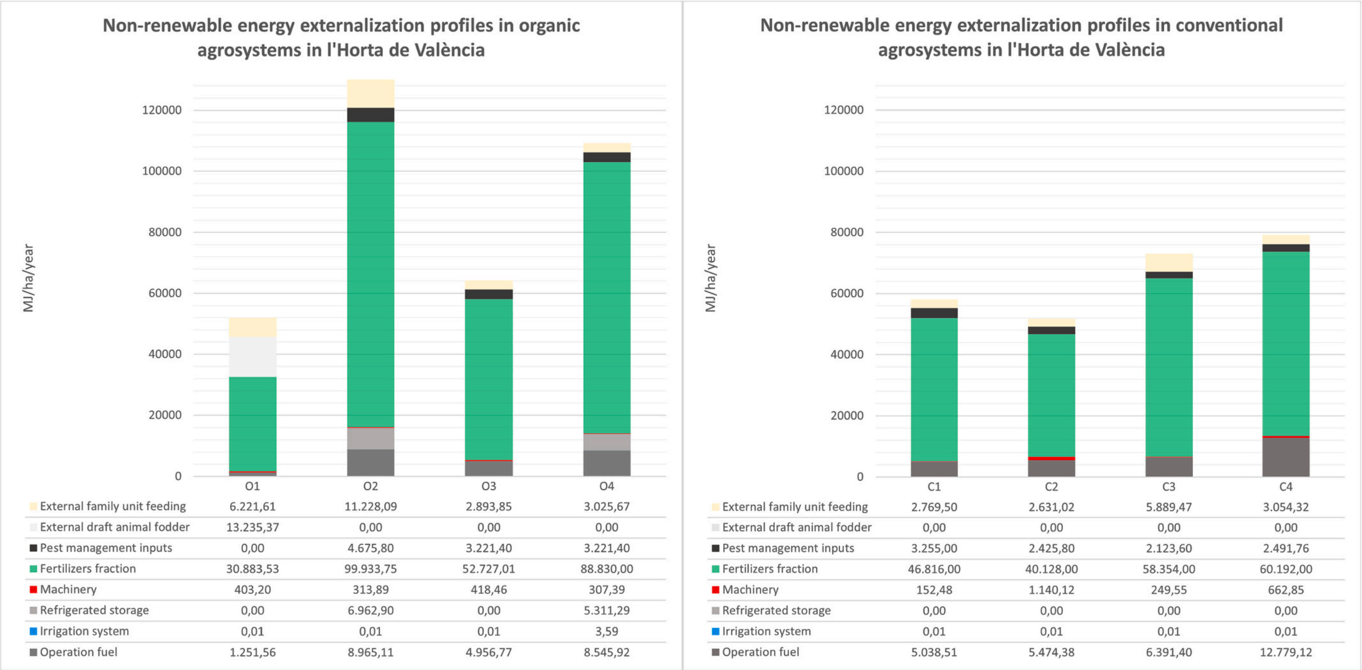
	C1	C2	C3	C4
🟩 HB (MJ ha-1 year-1)	55.369,01	34.067,63	91.885,82	26.572,49
■ REB (MJ ha-1 year-1)	2.769,50	2.631,02	64.243,47	3.054,32
■ Y (MJ ha-1 year-1)	3.414,02	3.206,85	6.243,50	7.692,81
− F1 (MJ ha-1 year-1)	52.006,99	46.742,51	6.640,96	73.633,97
▲ F2	0,07	0,07	0,94	0,10

Fig. 4. Total harvested biomass (HB), Recirculated external biomass (REB), commercial yield (Y) and fossilization index (F1, F2) for four organic (O) and four conventional (C) farms in l'Horta de València agroecosystems. Source: our own.
HB = Harvested Biomass; REB = recirculated external energy flow; Y = total annual yield; F1 = Agroecosystem flows non-recirculable fossil dependance index; F2 = Fossil Final EROI or Yield fossil dependance; O1…O4; organic farming sample coding; C1…C4; conventional farming sample coding.

not achieve, by far, the average surplus shown for organic farms. With respect to conventional farmers, NRE input on average is much lower when compared to organic ones, regardless of TPB surplus or deficit. Fewer crops per season -to reduce workload-, machinery and land owned in conventional farms -without the need to make investments or productive changes- together with the precarious financial situation of the citrus fruits farm-operators (C1,C2), are probably regulating the investment in fossil inputs. Such farms demonstrate indeed low economic return of the yield and therefore exert greater pressure on the natural fund, as noted by González-Molina et al. (2020), appyling for instance greater amounts of fertilizer per yield units than organic ones, while less pest mangement inputs per hectare. Following the hypothesis of Stratford (2020), the extraction of rents, together with a greater externalization of flows, could be mediating this depletion of the natural fund; a worrying situation in a context of fossil fuel constraints and resource scarcity (Harchaoui and Chatzimpiros, 2018). Nevertheless, this hypothesis must be further researched by enlarging the sample and study period.

The TPB deficit of organic operators in the sample, consistent with previous studies (Fess and Benedito, 2018), indicates an inverse situation, in which the maintenance of productivity, with several annual harvests, depends extremely -in sample- on external inputs (work, machinery, pest management external inputs, fertilizers and fuels). The results demonstrate that economic returns are supported by fossil fuels input, regardless of the management model. The intensive use of fossil-fuel input instead of recirculation within organic farm practices is consistent with certain studies (Alonso and Guzmán, 2010), but contradicts the results of other previous studies comparing agricultural practices (Pergola et al., 2013). In the absence of any further studies, the results point to a trend of industrialization of organic agricultural systems, and to an unintended greening of conventional ones in the l'Horta de València area. Other energy efficiency studies (Ramos-García et al., 2022) deepen into this 'unintended' performance of organic farming, revealing by means of multi-EROI assessment the several production models under common categories. These results may also contribute to the open discussion about limits and trade-offs of ecological or sustainable intensification, as explored by Guzmán-Casado and González-Molina (2017) and the robustness of agrarian models to input supply declines (Pinsard and Accatino, 2023).

Unlike the results obtained in benchmarking analyses between organic and conventional agriculture (Alonso and Guzmán, 2010; Pergola et al., 2013; Guzmán-Casado and González-Molina, 2017), in present study the productivity as yield (Y) is considerably higher in organic operators than in those identified as conventional, according with experimental results found in Suja et al. (2017). This situation might be the result of the different conditions referred to in their pre-identified typologies, such as less availability of approved inputs in organic farming (currently improved) and/or absence of incorporation of other practices such as rotations or green manures (extended and common practices for organic operators within study area). Subsequent studies analyzing these variables are therefore necessary to specify their significance on agroecosystem performance and management decision-making processes at farm operator scale.



	O1	O2	O3	O4
🟨 External family unit feeding	6.221,61	11.228,09	2.893,85	3.025,67
⬜ External draft animal fodder	13.235,37	0,00	0,00	0,00
⬛ Pest management inputs	0,00	4.675,80	3.221,40	3.221,40
🟩 Fertilizers fraction	30.883,53	99.933,75	52.727,01	88.830,00
🟥 Machinery	403,20	313,89	418,46	307,39
▨ Refrigerated storage	0,00	6.962,90	0,00	5.311,29
🟦 Irrigation system	0,01	0,01	0,01	3,59
■ Operation fuel	1.251,56	8.965,11	4.956,77	8.545,92

	C1	C2	C3	C4
🟨 External family unit feeding	2.769,50	2.631,02	5.889,47	3.054,32
⬜ External draft animal fodder	0,00	0,00	0,00	0,00
⬛ Pest management inputs	3.255,00	2.425,80	2.123,60	2.491,76
🟩 Fertilizers fraction	46.816,00	40.128,00	58.354,00	60.192,00
🟥 Machinery	152,48	1.140,12	249,55	662,85
▨ Refrigerated storage	0,00	0,00	0,00	0,00
🟦 Irrigation system	0,01	0,01	0,01	0,01
■ Operation fuel	5.038,51	5.474,38	6.391,40	12.779,12

Fig. 5. NRE externalization profiles for four organic (O) and four conventional (C) agroecosystems in l'Horta de València. Source: our own.
O1…O4; organic farming sample coding; C1…C4; conventional farming sample coding. Categories provided account for different inputs (see supplementary materials to detailed description).

5.2. From fossil-sink agricultures to fossil profiles: a key tool to deliver sustainable management options

Regarding the MEFA comparison between crops and energy analysis on farms, Mazis et al. (2021) find similar results with respect to externalization profiles by category, with fertilizers being the main energy pillar within the agroecosystem. It is important to note that there are several differences between the current study and that of Mazis et al. (2021). Here there are 1–4 crops per year per same area, with only 1 crop per area for Mazis et al. (2021). Furthermore, we applied a conservative criterion regarding the energy contained in inputs (including transport, production and energy for fuel extraction). Both organic and conventional farms have lower mechanization rates than those used in Mazis et al. (2021). Finally, in this study, the practice of using mainly external inputs for both types of farms shows greater variability (29,1%-83,6% for fertilizers). Such variability is possibly related to a greater variety of crops and farm systems analyzed (fruit trees, mixed horticultural, rice field and monoculture vegetable).

Our results of NRE profiles by categories and agricultural management show great dependency on fertilizers as a main external input within the agroecosystems (59–82% of CE), whether in organic or conventional operations. As stated in previous studies the use of fertilizers constitutes by far the largest energy contribution within farms (Smith et al., 2015; Kamali et al., 2017; Stylianou et al., 2020). Any reduction in type and quantity would significantly decrease the energy input, thus improving the efficiency of external inputs (EFEROI) and the final energy return of the farm (NPP_{act} EROI). With respect to external input efficiency in our case study, this index presents a great variability that does not strictly correspond to the pre-identification of farms as conventional (C) or organic (O). Our study sample performed better in relation to external investment ($\overline{EFEROI}$; 0,34–3) compared to the results of Galán et al. (2016) for El Vallés region (Catalonia) and better in terms of external input efficiency when compared to 2012 year value obtained for an agroecosystem in Mallorca in Fullana-Llinàs et al. (2021). Such results could be related to low mechanization, prevalence of some traditional agricultural practices within a few conventional farmers (workload, crop rotation, vegetable residues incorporation) and greater land productivity of l'Horta region compared with the El Vallés region. Efficiency of internal flows ($\overline{IFEROI}$; 0,94-1,46) in this study, are slightly lower than the value obtained in aforementioned publication. As stated by Tello et al. (2015), energy efficiency comparison between regions shows bias as it is also dependent on historic and territorial variables affecting soil productivity. Nevertheless, similar context-situation and EROI's performance (EFEROI, IFEROI) is described in Fullana-Llinàs et al. (2021) with respect to conventional farming's input allocation and industrialization between 1956 and 2012 in Mallorca. Unique source considered of socialized biomass in study area of l'Horta de València it's probably the cause of lower NPP_{act} EROI value when compared to previous cited study, instead of including woodland or socialized animal biomass as in Fullana-Llinàs et al. (2021) and Guzmán-Casado and González-Molina (2017). L'Horta de València constitutes a large area covered mainly by horticultural and fruits crops, with no significant use and presence of forest cover or livestock farming, along with scarce non-harvested biomass within the agroecosystem, unlike previous studies. Further research is needed to assess the evolution of NPP_{act} EROI in study area, as falling values over time indicate degradation of productive capacity of agroecosystems (Guzmán et al., 2018).

The specific index of agroecosystem fossil dependence (F1) and fossil EROI (F2) provides insight of the fossil-fuel fraction weight in substitution of recirculation processes observed within the agroecosystem and the relation of output yield units with respect to non-recirculated fossil fuel entry flow. Fossil EROI allows for a initial benchmarking of farmers which are net NRE consumer. We develop these indexes so in order to distinguish between 'energy-sink agricultures', as stated by González-Molina et al. (2020), and 'restorative agricultures', in which part of these non-renewable energies are dedicated to the transfer of materials and energy within internal agroecosystem processes. With respect of fossil-fuel allocation non-recirculated into the agroecosystem, first indicator reveals a higher dependence in conventional farmers. Some exceptions are noted, farmer (C3) does rely on this import (CE) in a similar degree compared to the rest of conventional farmers, whilst practices related to traditional triad crop management and fertilization enhances recirculation flows and render its energy performance similar to organic ones.

Indicator F2, or yield fossil-dependance, shows at least two trends: the first whereby this indicator is equal to or greater than 1 (sample majority), and the second where this ratio is close to 0 (C1,C2,C4). The results indeed show that the differences between the internal use of these NRE are related to practices considered traditional, and which are persistent in l'Horta area (despite agrarian industrialization) as stated in Fullana-Llinàs et al. (2021). Those farm-operators still making use of organic manure from locally-produced livestock (O1,O2,C4) recirculate up to 90% of the inputs. Aguilera et al. (2020) propose to enhance organic farming energy performance by means of the latter. This result is the opposite for farm-operators relying on mineral composite fertilizer, recirculating approximately 5%, as in the case of C2,C1,C4.

Regarding the importance of addressing fertilizer source, noted yet by several studies (Aguilera et al., 2015; Guzmán-Casado and González-Molina, 2017; Mazis et al., 2021) our findings reinforce conclusions of previous studies (Smith et al., 2015; Harchaoui and Chatzimpiros, 2018; González-Molina et al., 2020), as fertilizers represent the critical input to fossil-dependance in agroecosystems. Further research on landscape-based energy analysis is needed to assess range of maneuver for closing this main loop at a local scale: small farmplots and holdings, livestock critical absence from modern agroecosystems and increased workload are variables which hinder nowadays the transition to this practice in l'Horta de València area.

Special emphasis is needed upon the energy-profile and energy-return related to the use of draft animals, as they suppose an alternative to machinery use and external fertilization. As Tello et al. (2015), González-Molina et al. (2020) and Mosnier et al. (2022) pointed out, the disengagement between livestock and agriculture supposes an energy gap within farms, driven by the use of synthetic and/or organic fertilizers which heavily increases energy contribution through both transport and application (Li et al., 2017). Using draft animals in agroecosystems may potentially reduce the disengagement between agriculture and livestock, and improve, under certain conditions, energy performance, (Harchaoui and Chatzimpiros, 2018; González-Molina et al., 2020). But their use in small farms which cannot feed draft animals exclusively from the farmplot and which cannot benefit from complete draft power, may engender adverse results to input efficiency and energy profiles. In the case of O1, the only farm with draft livestock, external feed accounts for up to 25% of non-renewable inputs. The increase in size of organic farms, the leasing of machinery or daily workhorse loads, and the use of organic fertilizers are practices in line with a fossil-fuel detaching strategy within those agroecosystems at farmplot level.

5.3. Energy-management strategies: sustainability as a double agroecosystem condition

5.3.1. Productive-reproductive sustainability strategies in l'Horta de València agroecosystems

Fig. 6 shows productive-reproductive sustainability performance in the management of biomass, materials and energy flows for our sample farm-operators, or 'strategy', illustrating at least four different agricultural systems under two 'umbrella' categories, following Ramos-García et al. (2022).

The first category is made up of farm-operators pre-identified as medium-sized conventional and organic farms (O3,C1,C3), whereby current management practices result in positive balances between the actual net primary productivity and outsourcing fossil inputs (CE). Here the positive productive balance is achieved at the expense of relatively fewer units of fossil energy input, even though organic farmers perform better in terms of fossil EROI. Simultaneously, the reproductive behavior of the agroecosystem is extractive, as production is achieved by subtracting energy units from its reproduction flows. We have coined this strategy as a "dissipate and extract" strategy. Common economic

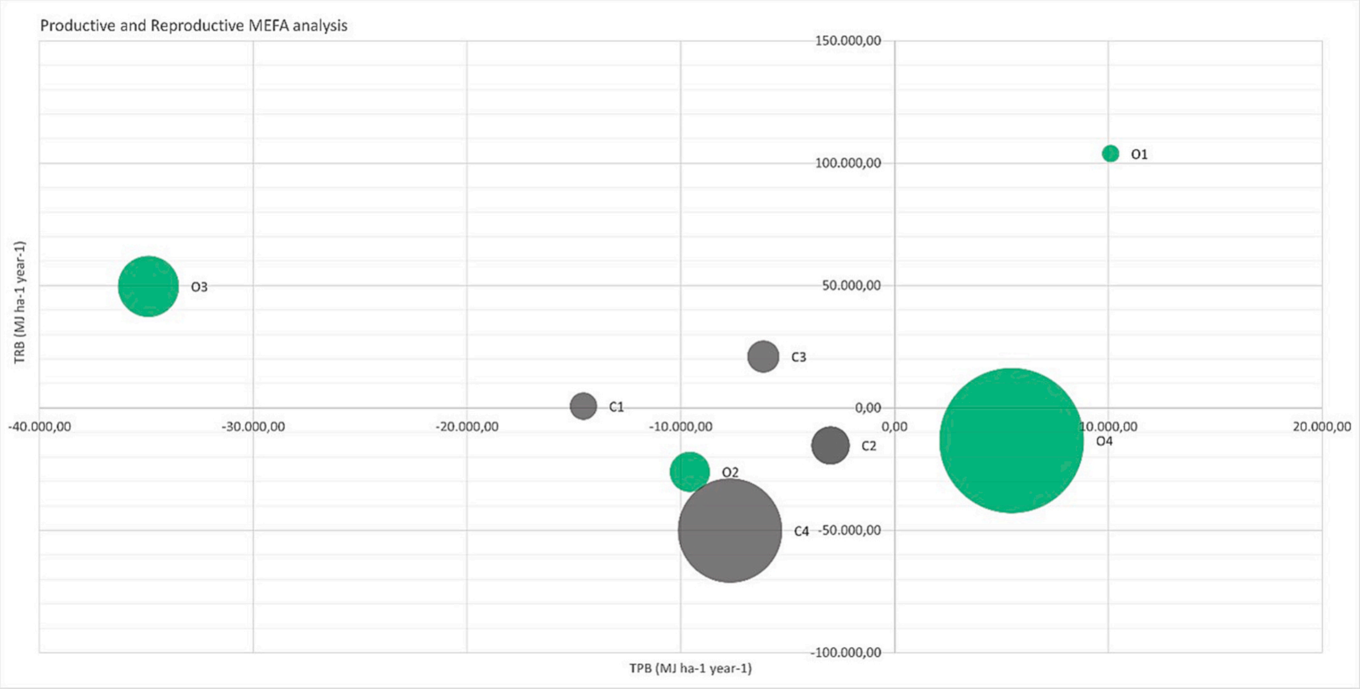


Fig. 6. Scatter plot analysis of MEFA matrix index TPB-TRB according to farm size for agroecosystems in l'Horta de València. Upper right quadrant shows 'dissipate and restore' strategy, upper left 'dissipate and extract', lower right quadrant corresponds to 'sink and restore' strategy, and lower left 'sink and extract' strategy. Source: our own.
TPB = Material and Energy synthetic balance between Actual Net Primary Productivity and total Non-renewable energy in agroecosystems (CE); TRB = Material and energy synthetic balance between internal biomass recirculation and total NRE (CE); O1…O4; organic farming sample coding; C1…C4; conventional farming sample coding.

performance is present for (C3) and (O3), with local retail distribution. Better labour performance is achieved by conventional (C3) regarding higher mechanization when compared to O3. Low labour-intensity of citrus fruits and falling agrarian market prices (Hermosilla-Plá and Membrado-Tena, 2018; López-García et al., 2021) explains labour and economic performance in (C1).

The second category is made up of farms under conventional practices (C2,C4) plus one medium-size organic farm (O2). Here the productive management strategy is deficient, as fewer energy units are achieved than those incorporated through externalization processes: an energy-sink agroecosystem profile. Simultaneously, the reproductive behavior is extractive (production subtracts energy units from its reproductive flows, to a degree similar to the previous strategy mentioned), and so this strategy can be defined as “sink and extract”. Similar multi-EROI ratios occur for O2 and C2, while higher yield and economic performance of organic local retail explains labour and economic performance. Better gross margin is found for C4 in sample. The last probably relates to high yield specialization and agrarian subsidies receipt.

The third strategy is represented by the largest exploitation in the sample (O4), which behaves in productive terms as a net sink, and in reproductive terms as a net repository. It therefore achieves a negative net production in energy terms with respect to fossil inputs, and simultaneously recirculates parts of these inputs in the agroecosystem recirculation processes, becoming a “sink and restore” strategy. This farmer performs also great in net revenues, while high investments in machinery, inputs and land downsize its gross margin. Following Guzmán and González-Molina (2015), it shows to which extent the intensification and high-external input organic agriculture performs in agroecological-energy perspective terms.

The fourth strategy is constituted by a single farm (O1) of small size, which behaves in productive terms as a net energy dissipator, and in reproductive terms, as a net recirculator. It does not subtract biomass and energy from the reproductive processes, but instead feeds them in part with external fossil flows, depending mainly on internal sourcing. We have coined this strategy as “dissipate and restore” strategy, or a “sustainable strategy” from an agroecological-energy perspective proposed by Guzmán-Casado and González-Molina (2017). Within this study and strictly from a farm-operator standpoint, such a “sustainable strategy” is defined as the allocation of inputs with productive output without compromising reproductive flows, following the approach of González-Molina et al. (2020), represented in Fig. 6 in the upper right quadrant. Economic performance is poor though, due to lack of access to agrarian subsidies and low incomes from sales.

Previous agrarian strategy drafts align with trends observed in Ramos-García et al. (2022) with respect to organic agriculture in Andalusia (Spain), where subsidy policies and agrarian prices may have lead to a ‘convencionalization’ of organic agriculture, by means of intensive fossil fuel use and depletion of reproductive flows. Nuances and diverse sustainability performance is shown in this study for both organic and conventional farming models, implying a need to comprehensively assess agrarian practices in terms of local decoupling, and also NRE use intensity and efficiency if sustainable transition agrarian models are to be promoted.

5.3.2. *Use of multi-EROI for drafting agrarian sustainability strategies*

Shifting patterns between external input (CE) and biomass recirculation (RB) are necessary to improve energy throughputs within agroecosystems (Tello et al., 2016b). In our study, most farm operators (O4, O2, C3, C1, C2, C4) requiere a lowering of externalization flows to sustain its productivity and reproductivity performance (see Fig. 7). Greater recirculation of materials and energy from internal processes would improve performance of conventional systems (C1, C2, C3, C4) and two organic farmers (O2,O4). Smaller scope possibility, in terms of balancing efficiency between joint inputs following Tello et al. (2016b), is calculated for O3 (NPP_{act} EROI, 0,81) and O1 (NPP_{act} EROI, 0,72).

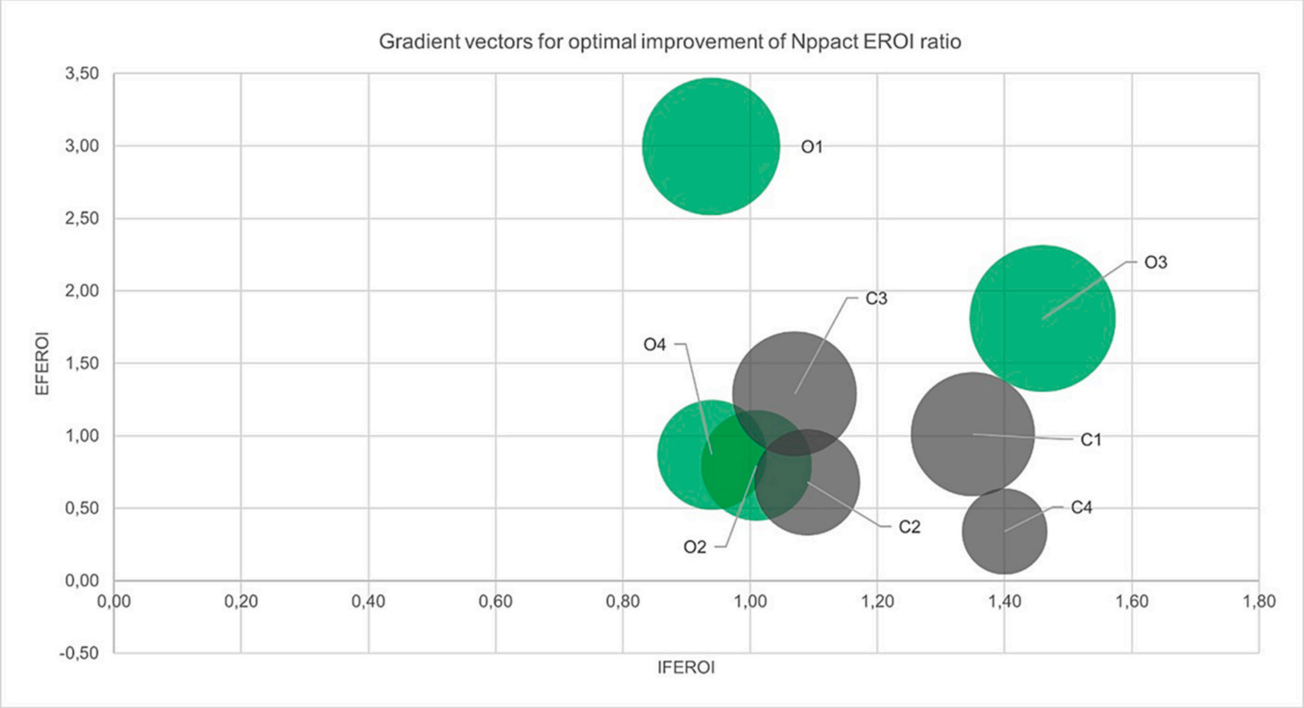


Fig. 7. EFEROI-IFEROI relation and gradient vectors for FEROI optimization in for organic (O) and conventional (C) agroecosystems of l’Horta de València. Source: our own based on Tello et al. (2016a).

EFEROI = External Flow Energy Return On Investment; IFEROI = Internal Flow Energy Return On Investment; RIB = recirculated internal biomass; REB = recirculated external biomass; Δ = variable change for optimizing gradient vectors. O1…O4; organic farming sample coding; C1…C4; conventional farming sample coding.

Here, both farms employ practices considered key in traditional smallholding operations: rotations, incorporation of crop residues, use of organic fertilizer, on-farm food consumption, high human workload and limited use of machinery. Both O1 and O3 broadly comply with the proposal put forward by Aguilera et al. (2020) outlining sustainable agroecological agriculture for Mediterranean region.

Combined use of energy thoroughput analysis allows to distinguish between farming practices leading to save external input per yield unit (LEIT strategy) as shown by (O1) farmer, and those willing to increase yield at the expense of more external input. Simultaneously, farming practice can either rely on maintaining yield over time through guaranteeing recirculation energy flows based on internal biomass reused (RIB) -demonstrated by most of the organic farmers, or by relying on external input short-term substitutions whilst avoiding declining yields (O3,C1,C4). The last pathway has been recently challenged by national-scale studies (Infante-Amate et al., 2014; Infante-Amate et al., 2015; González-Molina et al., 2020) though exceeds the present study scope. Further research on period benchmarking and long-term energy analysis are needed to address this question for the study area, along with labour, access to input alternatives and economic performance underpinning current practices and pathways.

Nevertheless and by means of joint analysis (see Fig. 7), results point to a reconsideration of agrarian sustainability pathways through the use of energy index, in order to address productive and reproductive dimensions. Traditional practices and the degree of fossil-fuel use should be accounted within agrarian sustainability analysis as they partly feature umbrella terms like ‘organic’, as in recent study carried out by Ramos-García et al. (2022).

5.3.3. *Further considerations on locally-adapted sustainable agrarian management possibilities from a farm-operator standpoint*

From the farm-operator’s standpoint, the management possibilities would include increasing the final production for each imported input, or reducing the inputs for each production unit (Tello et al., 2016b; Hoang-Khac et al., 2021). Based on this premise, and given the low yield revenues, amortization of machinery and land, and the productive decline of soils, all conventional farm-operators within the study are effectively restricting the inputs for each productive unit, and for the most part in an inefficient manner. Their unsustainable strategy can be defined as “sink and extract”. All three other strategies can only be considered sustainable by placing the limits of the agroecosystem at the limits of the farm plot itself (González-Molina et al., 2020), following Ramos-García et al. (2018), they are decoupled from their local agroecosystem. Indeed, such strategies imply the use of 1) external inputs to feed internal processes, 2) the non- substitution of labor inputs for machinery and 3) non-harvested biomass due to phytosanitary treatments. The use of draft animals for work and fertilizer (O1) is a minority strategy in the area, with its high labor costs and low economic performance, but represents the only strategy within the quadrant considered sustainable (“dissipate and restore”), and whose possibility scope -mainly in relation to economic sustainability - would not be identifiable from the gradient vectors. This highlights the need for further agrarian and metabolic studies regarding non-material variables affecting decision-making processes. An alternative strategy to the majority in the area “sink and extract” strategy, is one of reducing the IFEROI ratio while keeping EFEROI stable. This improvement strategy appeals mostly to conventional farms in the area who are facing diminishing agrarian returns and increasing prices for commodities as stated by López-García et al. (2021). Practices of internal recirculation of inputs through human/draft animal, NHB conservation-soil incorporation, crop rotation and organic manure application should be prioritized, as Aguilera et al. (2020) proposed for enhancing agrarian energy profiles.

The “dissipate and extract” strategy implies that strategic options for sustainable improvement might be the LEIT strategy (Tello et al., 2016b) or the reduction of externalization and fossil dependence (increase of EFEROI). As stated by Mazis et al. (2021), any management strategy employed by farms that implements alternative fertilization practices would become the most appropriate for significant reductions in external and fossil dependency. Nevertheless, as Guzmán-Casado and González-Molina (2017) point out, these practices may indeed present drawbacks, namely reduced economic return, precarious farm finances and additional workload (Marco and Tello, 2019), matching (O1) high labour EROI and low economic profile and may potentially explain for the other farms any reluctance in their implementation.

To inform comprehensive sustainability analyses that encourage a shift of agricultural practices and strategies, further studies are needed to assess the role of human and social capital in the productive and reproductive efficiency of farms (González-Molina et al., 2020; Hoang-Khac et al., 2021) as well as the pursuit of LEIT strategies within small farms (Tripp, 2005; Tello et al., 2016b). These agricultural practices and strategies can include crop substitution, fertilization and soil management (Guzmán et al., 2018; Stylianou et al., 2020) or the re-engagement of livestock and agriculture in mixed farms for the purpose of improving energy efficiency and sustainability (Harchaoui and Chatzimpiros, 2018; Hoang-Khac et al., 2021; Mosnier et al., 2022).

Also, detailed evaluations are needed of energy efficiency and outsourcing profiles in farms that broadly contemplate fossilization chains in agroecosystems. Such fossilization chains include direct and indirect energy (Fess and Benedito, 2018; Su et al., 2021) and also recirculating and non-recirculating systems (Tello et al., 2015). Comprehensive multi-EROI (Ramos-García et al., 2022) and agroecological energy analysis (Guzmán-Casado and González-Molina, 2017) becomes an useful tool (though currently non-applied) to conceive better agricultural farm managements and agrarian transitions as desired by European framework public policies (European Commission, 2020, 2020b, 2022).

6. Conclusions

Our results point to indirect fossil uses within agroecosystems as the main contributors to NRE dependency, particularly inputs associated with fertilization -both synthetic and from livestock farms- together with inputs associated with draft animal feed. Priority action areas in the transition towards sustainable agricultural systems in l’Horta València are therefore: (1) the substitution of certain practices (e.g., synthetic fertilizer, monoculture or historically repeated crop rotation, absence of fallow and systematic weed removal) by specific energy-recirculating practices (e.g., local and organic manure application, variable rotations, fallow, green cover crop and deliberate use of non-harvested biomass); (2) transition practices to enhance fossil-fuel detaching (e.g., increase workhorse load and ensure feeding within farm); (3) the adoption of strategies for the disengagement of indirect fossil energy use, mainly due to natural-fund enhancement by means of non-harvested biomass, fertilization strategy and soil recovery practices.

With respect to the possibility of implementing sustainable management practices on conventional farms, our results point to the need of a strategy orientated to solving precarious financial situations and diminishing agrarian returns. The issues to be addressed at farm-plot level, such as crop rotation, fallow land, and incorporating waste and organic manure, are often considered to be traditional and sometimes outdated agricultural practices, but their implementation will lead to substantial improvements both in the energy profile of the exploitation and in soil fertility.

Probably, agrarian land property and intensive management system in l’Horta de València becomes a drawback when aiming to recirculate material and energy flows within the agroecosystem through single farmer’s point of view, when aiming to mainstream some practices such as draft animal use and local organic manure provisioning. Priority action areas to be considered are (1) to avoid conventionalization of organic farming by means of intensive fossil-fuel use, or by placing the limits of the agroecosystem within the farmplot itself (2) to encourage fossil-detaching practices in conventional agriculture, mostly those associated to traditional agrarian management, while ensuring social and economic sustainability and livelihood of the conventional farmers (3) to develop agrarian and land planning public policies fit to overcome the private owner interest while suitable to enhance the recirculation of flows at a landscape level. Eventually, if agrarian sustainability transition within European framework aims to solve agrarian low efficiency of inputs while ensuring agroecosystem's reproduction, it is crucial to avoid an unintended greening of conventional systems and an industrialization of organic ones, by means of economic revenues.

The energy profiles and the fossilization indicators proposed in this study allow the selection of sustainability criteria based on productive and reproductive conditions for agroecosystems, and which have direct application to agricultural producers at the farm scale. This constitutes an advance in research at the farm-plot analytical level, particularly with respect to fossil energy (in)dependence, and improving sustainability within agroecosystems. Subsequent studies are now necessary to help design models focused upon landscape agrarian metabolism in the area. Such models need to integrate social, environmental and economic variables which will be beneficial in the identification of strategies and indicators of productive and reproductive improvement at farm-operator scale.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2023.108069.

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