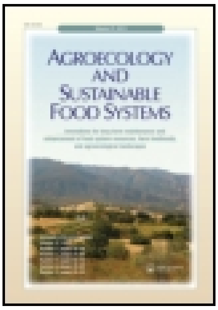

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David Pérez Neira [a], Marta Soler Montiel [b] & Xavier Simón Fernández [c]

[a] Department of Economics and Quantitative Methods, University of Pablo de Olavide, Sevilla, Spain

[b] Department of Applied Economics II, University of Sevilla, Sevilla, Spain

[c] Department of Applied Economics, University of Vigo, Vigo, Spain

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Energy Analysis of Organic Farming in Andalusia (Spain)

DAVID PÉREZ NEIRA,[1] MARTA SOLER MONTIEL,[2] and XAVIER SIMÓN FERNÁNDEZ[3]

[1]*Department of Economics and Quantitative Methods, University of Pablo de Olavide, Sevilla, Spain*
[2]*Department of Applied Economics II, University of Sevilla, Sevilla, Spain*
[3]*Department of Applied Economics, University of Vigo, Vigo, Spain*

High oil dependence and energy inefficiency are structural characteristics of industrialized agricultural systems. In a context of climate change and growing energy shortage as the present one, energy indicators should be increasingly taken into account as measures of environmental sustainability, efficiency, and technical-productive viability in analyses and decision-making processes in the field of agriculture. One of the most relevant characteristics of agriculture is its capacity to transform energy and to generate an energy "surplus" that has very diverse uses (human feeding, animal feeding, fertilization, etc.). This energy surplus is potentially greater in organic farming. However, empirical studies analyzing the aggregate energy performance of organic farming and allowing an assessment of the scope and energy limitations of this type of production are few. This work analyses the energy performance of organic farming in Andalusia, the southern region of Spain, both in an aggregate form and by large groups of crops, through the energy assessment of its output, inputs and energy efficiency (ER). The energy ratio of Andalusian organic farming in 2005 was estimated by 1.40, the extensive crops (2.86), horticultural crops (0.18), citrus fruits (0.39), subtropical fruits (0.85), other fruits (1.64), nuts (0.54), olive (2.08), and vine (0.76).

KEYWORDS *Agricultural energy analysis, energy efficiency, organic farming, sustainable agriculture*

Address correspondence to David Pérez Neira, Universidad Pablo de Olavide; Edificio N°3, Conde de Floridablanca, Ctra. de Utrera, Km.1, 41013 Sevilla, Spain. E-mail: dpernei@upo.es

1. INTRODUCTION

The efficient use of energy resources is one of the most important aspects when it comes to thinking of the most sustainable food production systems (Meul et al. 2007). High oil dependence and energy inefficiency are well-known structural characteristics of industrialized agricultural systems that have been studied for more than four decades (Odum 1967; Pimentel et al. 1973; Leach 1976). In the last few years, agricultural energy consumption, far from diminishing, has progressively increased (Simón Fernández 1999; Venturi & Venturi 2003; Karimi et al. 2008; Khosruzzaman et al. 2010; Ghorbani et al. 2011; Ozkan 2011) with the subsequent environmental impacts, among which climate change is one of the most prominent (West and Marland 2002; Hatirli et al. 2006; Mohammadi and Omid 2010). Energy efficiency cannot be the only factor to take into consideration in relation to human food systems. Nevertheless, energy analyses reinforce the comprehension of the functioning of agricultural systems in technical-productive and economic decision-making processes and contribute to the search for viable energy alternatives in agriculture. Therefore, in the context of the current growing energy shortage and environmental fragility, energy analyses of agricultural systems—as an analysis methodology—are called into play with an increasingly important role in agrarian studies (Dalgaard et al. 2001).

Nowadays, one of the main foci of the debate on agriculture is the need to present evidence of how and to what extent organic farming can be a sustainable alternative for food production (Altieri 1987; Altieri and Nichols 1999; Gliessman 2000, 2001; International Federation of Organic Agriculture Movement [IFOAM] 2011), and, particularly, of the better energy performance of this type of production as compared to that of conventional agriculture (Minister of Agriculture, Fisheries and Food 2000; Pimentel 2006; Ziesemer 2007) and in relation to the fight against climate change (Borron 2006; Badgley et al. 2007; LaSalle 2008; El-Hage and Muller 2010; Muller 2009).[1] These academic contributions have been made while the area, production, and employment associated with organic farming activities has kept increasing globally (Weidmann et al. 2011; Willer 2011).

After some pioneering works in the 1970s and 1980s (Berardi 1978; Pimentel et al. 1983; Dazhong and Pimentel 1984; Lockeretz et al. 1984; Pimentel 1993), energy analysis applied to organic farming has developed in the last 15 years through case studies on specific crops (wheat, corn, and potato by Pimentel et al. [1991]; olive by Kaltsas [2007]; carrot and onion by Ministerio de Medio Ambiente y Medio Rural y Marino [MARM; 2000], and orange by Peris and Juliá [2006]) or based on empirical data collected on farms, such as the study on Turkish apricot production (Gündoğmuş and Bayramoglu 2006) or the systems in the United Studies (Bailey et al. 2003). Many comparative studies focused on analyzing the energy improvement of organic crops in relation to conventional agriculture (Berardi 1978; Dalgaard et al. 2001; Hoeppnera et al. 2006; Grönroos et al. 2006; Deike et al. 2008; Ghorbani et al. 2011) have also been published. Complementarily, the improvement of energy efficiency in the transition from industrial agricultural systems to ecological management has also been widely documented (Gündoğmuş 2006; Pimentel 2006; Klimeková and Lechocká 2007; Ziesemer 2007).

In Spain, early energy analysis studied agriculture in aggregated terms in a region, such as Extremadura (Campos and Naredo 1978) and Andalucía (Campos and Naredo 1980), and at the country level (Naredo and Campos 1980), showing the loss of energy efficiency as a consequence of agrarian industrialization. Simón Fernández (1999) and Carpintero and Naredo (2006) update Spanish agriculture energy data. Regional agrarian energy studies have been realized from a historical perspective in Catalonia (Cusso et al. 2006) and Andalusia (Guzmán and González de Molina 2006). Energy analysis of organic farming in Spain have also focused on comparative studies of specific crops and products such as olive oil (Guzmán Casado and Alonso Mielgo 2008) or citrus fruit and horticultural crops (Roselló-Oltra et al. 2000; Lacasta and Meco 2000).

However, until today regional and sectorial energy analyses of organic farming based on empirical data allowing a better comprehension of the energy performance of this activity as an economic sector are still rare. The analysis of organic farming based on energy indicators is a fundamental dimension of the analysis of the sustainability of agricultural systems in biophysical terms. In a context of climate change and energy shortage as in the present, the comprehension of the energy performance of agricultural systems is essential both for technical-productive decision-making and for the design of alternative food production models (Dalgaard 2001).

In Spain, organic farming is a consolidated sector that has not stopped growing in the last few years. The area certified as devoted to this activity in Spain has increased from 4,235 ha in 1991 to 1,650,866 ha in 2010 (MARM 2011). Thus, Spain is the EU-15 country with the largest organic crop area in absolute terms, contributing 20% of the European organic farming area (Forschungsinstitut für biologischen Landbau [FiBL] 2011). In addition, Andalusia is the Mediterranean region with the largest organic crop area in Spain, which represents more than 50% of the total national area (MARM 2011).

In this sense, the objective of this work is to contribute to the debate on the energy performance of organic farming and, particularly, to analyze the energy performance of the organic farming sector in Andalusia through the application of the energy analysis methodology. With this purpose, organic farming is studied in relation to its output, inputs (direct energy, indirect energy and capital energy), and energy efficiency, as well as other energy indicators, both in an aggregate manner and by large groups of crops (extensive crops, horticultural crops, citrus fruits, nuts, subtropical fruits, other fruits, vines, and olive). The selection of the period of reference (year 2005) has to do with the availability of information and data: 2005 was the only year for which complete data on the physical and economic performance of the ecological sector as a whole, both in Andalusia and in the rest of the Spanish territory, were available (Soler et al. 2009). Despite the limitations inherent to the analysis of one sector or economic activity in relation to a single period of time, this study aims to make a first comprehensive view allowing an assessment of the scope and limitations of the energy efficiency of organic farming in Andalusia as a fundamental requirement for environmental sustainability, as well as the identification of those areas on which research needs to focus and of the technical-productive changes required to progress towards greater energy efficiency.

2. MATERIALS AND METHODS

The energy assessments presented in this article are based on the empirical data provided by 250 organic farms surveyed in 2006–2007. These data were also the basis for the monetary estimation of the "Economic Accounts of Organic Farming and Stockbreeding in Andalusia in 2005" (Pérez-Neira et al. 2007).[2] The cultivated area studied in this work represented 20.5% of the total certified ecological area in Andalusia that year (2005), that is, 81,825 ha out of the total 403,360 ha. The rest of the certified area, covered by forests (40%) and grassland and meadows (39.5%), was not included in the study (Dirección General de Agricultura Ecológica 2007). The year 2005 was an atypical agricultural year with heavy frosts and floods that considerably affected and reduced the harvest of some crops, but it was the only year for which the necessary information to undertake a wide-scope empirical energy study as that presented here was available.

Energy estimations have been made both by types of crops and for the whole sector of organic farming. For simplicity purposes, the crops are classified into eight large groups reflecting the main crops of organic farming in Andalusia: extensive crops (rice, oats, barley, sorghum, wheat, sunflower, chickpeas, broad beans, common vetch, peas, and the rest of the leguminous species); horticultural crops (garlic, artichoke, aubergine, courgette, pumpkin, cabbage, cucumber, melon, celery, broccoli, onion, beans, lettuce, pepper, tomato, potato, and carrot); citrus fruits (lemon, orange, tangerine, and hybrid citrus fruits); subtropical fruits (avocado, kaki, custard apple, and mango); nuts (almond and chestnut); other fruits (cherry, peach, apple, walnut, quince, etc.); olive (olives), and vine (grapes).

Every energy analysis implies at least three decisions at three different stages of the methodological design: 1) the definition of the limits of the system that is analyzed; 2) the identification of the parameters involved in that process and the assignment of weights or energy converters; and 3) the definition of the energy indicators. The methodological decisions previous to the energy assessments in this work are explained in the following section.

2.1. The Definition of the System Limits

The methodology used in this paper is the process energy analysis (International Federation of Institutes for Advanced Study [IFIAS] 1974; Corr et al. 2003; International Organization for Standardization [ISO] 2006; Meul et al. 2007; Udo de Haes 2007). In practice, energy analyses make a partial application of the principles of lifecycle analysis and the calculated system levels vary from one study to the other. These methodological decisions can be justified by various reasons associated to the relevance and availability of data. The system limits defined in the analysis of Andalusian organic farming presented in this article are summarized in Figure 1 and structured into five levels, four of them related to the energy inputs and a fifth one corresponding to the energy output.

Level 0 corresponds to the energy output measured by the gross agricultural production. Biological processes in combination with solar energy and photosynthesis generate an energy output (net primary production) that is available for the rest of the trophic network and partly captured by humans in the form of agricultural production. Level 1 quantifies the consumption of direct energy (DE) on the farm. Level 2 measures the consumption of indirect energy (IE), particularly the energy cost of producing the inputs used during the agricultural production process. Levels 3 and 4 quantify the proportional energy cost linked to the consumption of fixed capital (CE), in particular the consumption of energy associated with the amortization of machinery (level 3) and the repairing and maintenance of the fixed capital (level 4). The consumption of energy related to farm facilities and the transport of inputs and output has not been considered due to the lack of the necessary physical data for its calculation.

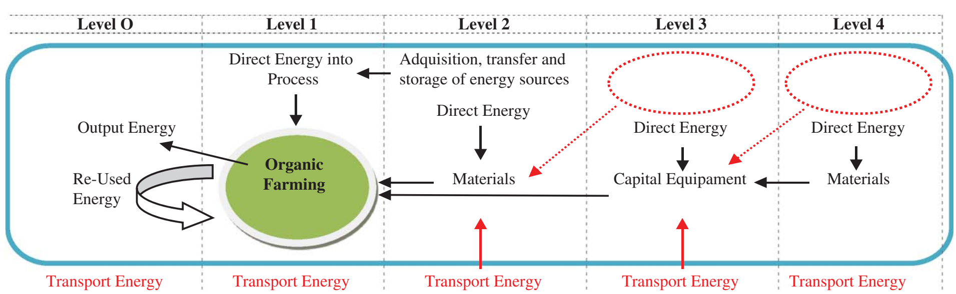

FIGURE 1 Analytical limits of the organic farming system in Andalusia (color figure available online).

2.2. Output and Input Parameters and Mass-Energy Equivalence

The agricultural output has been valued according to the energy contents of its total weight. The energy assessment of the agricultural output is based on the nutritional study by Moreiras et al. (2005), which introduced mass-energy (MJ kg^{-1}) converters by crops (i).

$$\text{Energy Output (EO)}_{(i)} = \text{agricultural output (AO)}_{(i)}\,(\text{kg}) \times \alpha^{-1}(i)\,(\text{MJ unit}^{-1}) \quad (1)$$

where $AO_{(i)} = \sum$ sales (kg) + intra-unit consumption (kg) + seeds (kg) + own-account final consumption (kg); i: type of crop; $\alpha_{(i)}$: energy converter of crop *i*.

In the case of the inputs, the energy assessment is made for each crop *i* by implementing the following equation:

$$\begin{aligned}\text{Gross Energy Requiriments (GER)}_{(ji)} &= \sum \text{Input (I)}_{(ji)}\,(\text{unit}) \times ß_{(j)}^{-1}\,(\text{MJ unit}^{-1})\\ &= \sum \text{direct energy (DE)}_{(ji)}\,(\text{MJ}) + \text{indirect energy (IE)}_{(ji)}\,(\text{MJ}) \quad (2)\\ &+ \text{capital energy (CE)}_{(ji)}\,(\text{MJ}).\end{aligned}$$

where ij: input *j* (diesel, manure, labor, machinery . . .) of crop *i*; I: input (physical unit); $ß_{(j)}$: energy converter of input *j*.

The energy assessments of agricultural inputs on levels 1 and 2—direct energy consumption and indirect energy consumption, respectively—have been made by using average energy converters ($ß_{(j)}$) calculated by following the indications of specialized literature and summarized in Table 1.

The energy assessment of the consumption of capital linked to the production, repairing, maintenance and replacement of machinery (levels 3 and 4) has been made with the use of the average energy converters summarized in Table 2.

2.3. Selection of the Synthetic Indicators for the Energy Analysis of Agriculture

The energy analysis of organic farming in Andalusia has been made by using synthetic indicators linked to the sector's output, inputs and energy efficiency by crops groups (i) as defined in the following equations (IFIAS 1974; Canakci et al. 2005; Yilmaz et al. 2005; Demircan et al. 2006; Ghorbani et al. 2011).

$$\text{Energy Productivity (EP)}_{(i)} = \text{energy output (EO)}_{(i)}\,(\text{MJ}) \times \text{area}^{-1}(\text{A})_{(i)}\,(\text{ha}) \quad (3)$$

TABLE 1 Agricultural inputs and energy coefficients ($ß_{(j)}$) on levels 1 and 2

Particulars A. Inputs	Unit	Energy equivalent (MJ unit^{-1}) Level 1 (DE)	Energy equivalent (MJ unit^{-1}) Level 2 (ID)	References
1. Seeds				
2. Purchase of seeds				
(a) Extensive crops	kg	GE Crop *i*	5.03	Fluck 1992; Pimentel and Pimentel 1996; Naredo and Campos 1980; Singh 2000; Moreira et al. 2005; Pérez-Neira 2010
(b) Horticultural crops	kg	GE Crop *i*	2.63	
3. Reuse of seeds	kg	GE Crop *i*	–	
4. Horticulture seedlings	seedling	–	0.20	Pellizzi 1992
5. Eco crop protection	kg	–	43.12	Helsel 1992; Roselló-Oltra et al. 2000; Singh 2000; 2005; Karimi et al. 2008; Mobtaker et al. 2010; Yilmaz et al.
6. Fertilization				
(a) Manure	kg	1.32	–	Sing 1986; NAAF 2000; Mclaughlin et al. 2000; Jiambo 2006; Khosruzzaman et al. 2010; Jarach 1985; Pérez-Neira 2010; Leach,1976; Pimentel 1980; Fluck 1992; Kaltsas et al. 2007
(b) Purchase of compost	kg	1.32	0.11	
(c) Other forms of fertilization	kg	–	4.96	
6. Diesel	kg	39.27	9.52	Cervinka 1980; Fluck 1992; Pimentel 1996; Tippayawong, 2003; Yilmaz et al. 2005; Canakci and Akinci 2006;Hatirli et al. 2006; Meul el al. 2007; Karimi et al. 2008; Sheikh Dovoodi and Houshyar 2009; Garavand et al. 2010; Higo and Dowaki 2010
7. Oils and lubricants	kg	–	67.25	
8. Plastics	kg	–	92.23	
9. Tools				
(a) Iron	kg	–	84.58	Tsatsarelis 1992; Pellizzi 1992; Baird et al. 1997
(b) Plastic	kg	–	92.23	
(c) Wood	kg	–	2.50	
10. Electric power	kw-h^{-1}	4.05	8.22	Jarach 1985; Kitani 1999; ; Ozcan et al. 2004; Meul et al. 2007; Mobtaker et al. 2010
11. Labor	kg	0.58	2.333	Stout 1990; Gajaseni 1995; Demarcan et al. 2006; Hatirli et al. 2006; Kizilaslan 2009; Pérez-Neira 2010; Ozcan 2011

TABLE 2 Fixed capital and energy coefficients ($ß_{(j)}$) on levels 3 and 4

Particulars B. Capital inputs	Unit	Energy equivalent (MJ unit^{-1}) Level 3	Energy equivalent (MJ unit^{-1}) Level 4	References
1. Machinery				Dazhong 1984; Doering 1980; Fluck 1992; Hetz 1992, 1998; Gajaseni 1995; De et al. 2001; Canakci et al. 2005; Yilmaz et al. 2005; Hatirli et al. 2006; Guzmán Casado and Alonso Mielgo 2008; Asakereh et al. 2010; Canacki 2010
(a) Large machinery (>50 CV)	Kg	80.5	41.9	
(b) Small machinery (<50 CV)	Kg	53.5	13.9	
2. Renting of machinery				
(a) 60 CV	H	13.4	6.9	Bonnie 1987; Doering 1980; Fluck 1992; Hetz 1992 and 1998; Pelizzi 1992; Yilmaz et al. 2005; Hatirli et al. 2006; Guzmán Casado and Alonso Mielgo 2008; Karimi et al. 2008; Asakereh et al. 2010
(b) 80 CV	H	16.1	8.4	
(c) 90 CV	H	19.1	10.0	
(e) 120 CV	H	22.3	11.6	

$$\text{Gross Energy (GE)}_{(i)} = \sum \text{direct energy (DE)}_{(i)}\,(\text{MJ}) + \sum \text{indirect energy (IE)}_{(i)}\,(\text{MJ}) + \sum \text{capital energy (CE)}_{(i)}\,(\text{MJ}) \tag{4}$$

$$\text{Net Energy (NE)}_{(i)} = \text{EO}_{(i)}\,(\text{MJ})\_\text{GER}_{(i)}\,(\text{MJ}) \tag{5}$$

$$\text{Energy Ratio (ER)}_{(i)} = \text{EO}_{(i)}\,(\text{MJ}) \times \text{GER}^{-1}_{(i)}\,(\text{MJ}). \tag{6}$$

GE and ER indicators have been calculated on the bases of nonrenewable energy (Ghorbani et al. 2011). Renewable energy comprises biomass gross energy (manure, compost, etc,), human work energy, as well as direct and indirect energy from renewable energy sources (wind and hydroelectric power and solar energy mainly). Consequently:

$$\text{Nonrenewable Gross Energy Requirements (GERnr)}_{(i)} = \sum \text{nonrenewable direct energy (DEnr)}_{(i)}\,(\text{MJ}) + \sum \text{nonrenewable indirect energy (IEnr)}_{(i)}\,(\text{MJ}) + \sum \text{nonrenewable capital energy (CEnr)}_{(i)}\,(\text{MJ}) \tag{9}$$

$$\text{Nonrenewable Energy Ratio (ERnr)} = \text{EO}_{(i)}\,(\text{MJ}) \times \text{GERnr}^{-1}_{(i)}\,(\text{MJ}). \tag{10}$$

TABLE 3 Energy assessment of the output of organic farming (energy output)

Items	Unit	Extensive crops	Horticultural crops	Citrus fruits	Subtropical fruits	Other fruits	Nuts	Olive	Vine	Weighted average
Area	1000 ha	16.21	1.49	1.23	0.53	0.49	19.84	41.52	0.49	81.83
Output	1000 t	17.56	30.49	20.65	3.15	2.88	5.23	55.56	1.96	137.46
Yield	$t \times ha^{-1}$	1.08	20.43	16.73	5.91	5.77	0.26	1.34	3.94	1.68
EO	GJ	381,158	32,782	30,463	25,536	9,058	90,284	563,851	5,093	1,138,225
EP	$GJ \times ha^{-1}$	23.5	22.0	24.7	47.9	18.1	4.5	13.6	10.2	13.9

3. RESULTS: ENERGY ASSESSMENT OF ORGANIC FARMING IN ANDALUSIA IN 2005

3.1. Energy Output

The organic crops studied covered 81,825 ha producing 137,464 tons of agricultural products equivalent to 1,138,225 Giga Jules (GJ) of energy. Olives were the crop making the largest contribution to the energy output (49.5%) (13.6 GJ ha^{-1}), as a result of both their territorial importance (they covered 50.7% of the total area) and the relatively high energy content of their fruit (9.46 MJ kg^{-1}). Extensive crops, the second group of crops according to their relevance in terms of energy, contributed 33.5% of the total energy while covering 19.8% of the total area (23.5 GJ ha^{-}). Nuts (almonds and chestnuts) were the third most important group in terms of energy, and they contributed 7.9% of the energy, which they generated on 24.3% of the total area (4.5 GJ ha^{-1}) (Table 3).

The remaining groups of crops have a much reduced energy weight in relation to the whole organic farming sector. Subtropical fruits (47.9 GJ ha^{-1}), citrus fruits (24.7 GJ ha^{-1}), and horticultural crops (22.0 GJ ha^{-1}) are the groups with the largest energy productivity. Nevertheless, the small size of the area they cover (4.2% of the total) results in their reduced weight in terms of aggregate energy. Other fruits and vines are characterized by average energy yields (18.1 GJ ha^{-1} and 10.2 GJ ha^{-1}), as a consequence of average and low agricultural yields, respectively.

3.2. Energy Input

The gross energy requirements of organic farming in Andalusia in 2005 were estimated at 814,268 GJ (9.95 GJ ha^{-1}) (Table 4). The crops with stronger territorial presence were the ones playing the most determinant role in the aggregate energy cost, although at the same time they were the crops with lower GER per ha. Thus, olives represented 33.3% of the energy cost with a consumption of 6.53 GJ ha^{-1}, extensive crops contributed 16.4% of the energy cost with an average consumption of 8.22 GJ ha^{-1}, while nuts represented 13.2% of the energy cost with average energy consumptions of 5.40 GJ ha^{-1}. The territorial importance of these crops, which jointly represented 94.8% of the total area under study and compensated their low energy intensities.

On the other hand, horticultural crops, citrus fruits, and subtropical fruits were the groups with higher GER per ha, well above the average. The high energy requirements of horticultural crops (121.61 GJ ha^{-1}) compensated the reduced area they covered and made of this group the second one in energy consumption: they concentrated 22.3% of the total consumption of organic farming in Andalusia that year. Citrus fruits and subtropical fruits played a less important role in energy costs (9.7% and 3.7%, respectively), despite

TABLE 4 Aggregate energy assessment of the inputs of organic farming

Types of energy	Unit	Extensive crops	Horticultural crops	Citrus fruits	Subtropical fruits	Other fruits	Nuts	Olive	Vine	Weighted average
Direct energy	GJ ha^{-1}	5.45	53.52	36.37	26.80	4.28	3.49	4.39	5.15	5.91
Indirect energy	GJ ha^{-1}	2.51	54.45	21.36	20.29	2.94	1.63	1.67	6.48	3.24
Capital energy	GJ ha^{-1}	0.27	13.65	6.20	8.99	3.83	0.28	0.47	1.89	0.80
Nonrenewable gross energy	GJ ha^{-1}	4.63	86.67	37.76	40.35	9.52	4.97	4.38	9.96	6.88
Gross energy requirements	GJ ha^{-1}	8.23	121.61	63.94	56.08	11.04	5.40	6.53	13.52	9.95

their high energy intensities (respectively 63.93 GJ ha^{-1} and 56.08 GJ ha^{-1}). Other fruits and vines were groups of crops with medium-to-low energy intensities (11,04 GJ ha^{-1} and 13,52 GJ ha^{-1}, respectively), slightly above the sector's average, but of little relevance in relation to the aggregate energy cost (0.7% and 0.8%, respectively) as a result of their limited cultivation area.

More than half the energy input of organic farming in Andalusia in 2005 (59.4%) was direct energy consumed at the farm, 32.6% was indirect energy linked to the inputs incorporated into the process and the remaining 8% was capital energy related to the machinery that was used. These results were not homogeneous and varied depending on the group of crops. Thus, for example, in those horticultural crops with higher energy intensities, 44% of the energy requirements corresponded to direct energy, 48.8% to indirect energy and 11.2% to capital energy. A similar distribution is found in other crops with high energy intensities, like subtropical fruits and citrus fruits. On the opposite end, low energy intensity crops, like olives, nuts, and extensive crops, were characterized by the important role of direct energy consumption at the farm. Thus, for example, direct energy represented 67.3% of the total energy cost of cultivating olive trees, while indirect energy contributed 25.6% of that cost and capital energy only 7.2%.

Almost one third of the overall energy expenditure of organic farming (30.1%) corresponded to renewable energy, mainly linked to organic fertilization, the only one allowed in organic farming. Therefore, the greater part of the energy requirements of organic farming in Andalusia (69.1%) was provided by nonrenewable energy.

The energy assessments of the different agricultural inputs are summarized in Table 5. Three groups of inputs (diesel and other oil derivatives, fertilization, and electric power) represent 80% of the gross energy requirements of Andalusian organic farming in 2005.

The largest energy expenditure is associated with the use of diesel as fuel for machinery (and other oil derivatives, like oils and plastics (4.40 GJ ha^{-1})), which jointly represent 44.2%[3] of the gross energy requirements of this sector. Fertilization is the second input in terms of energy (2.56 GJ ha^{-1}), and represents 25.7% of the gross energy requirements as a result of adding the DE of manure, the DE and IE of compost and the IE of other fertilizers permitted in organic farming (2.56 GJ ha^{-1}). The greatest energy cost corresponds to the use of DE in the form of manure, which represents 19% of the total GER. The consumption of electric power (1.09 GJ ha^{-1}) contributes 11% of the GER. The highest consumption of electric power is the one associated to water pumping in irrigation systems, which are frequent in the case of horticultural crops, citrus fruits, and olive trees cultivated in the plain.

The remaining agricultural inputs have a comparatively low weight in terms of energy: a total 19.1% of the GER of organic farming. The use and renting of machinery represents 8% of the GER (0.79 GJ ha^{-1}). The GER of seeds amounts to 5% of the total (0.50 GJ ha^{-1}), while the GER of horticulture

TABLE 5 Gross energy requirements by inputs and groups of crops (GJ ha^{-1})

Inputs	Unit	Extensive crops	Horticultural crops	Citrus fruits	Subtropical fruits	Other fruits	Nuts	Olive	Vine	Weighted average
Seeds	GJ ha^{-1}	2.47	0.54	–	–	–	–	–	–	0.50
Saplings	GJ ha^{-1}	–	3.40	–	–	–	–	–	–	0.06
Fertilization	GJ ha^{-1}	2.39	36.42	23.00	9.75	0.26	0.04	1.94	2.03	2.56
Protection	GJ ha^{-1}	0.00	4.57	4.81	0.38	0.09	–	0.18	3.39	0.27
Electric power	GJ ha^{-1}	0.32	17.76	15.86	23.09	0.36	0.57	0.32	1.93	1.09
Oil and derivatives	GJ ha^{-1}	2.72	42.80	13.07	12.74	5.31	4.28	3.36	3.50	4.40
Labor	GJ ha^{-1}	0.03	2.09	0.76	0.89	0.91	0.17	0.23	0.77	0.23
Tools	GJ ha^{-1}	0.02	0.38	0.24	0.25	0.27	0.06	0.03	0.01	0.05
Machinery	GJ ha^{-1}	0.01	12.68	6.14	8.98	3.39	0.04	0.37	1.87	0.61
Renting of machinery	GJ ha^{-1}	0.26	0.97	0.06	0.01	0.44	0.24	0.10	0.03	0.18
Weighted average	GJ ha^{-1}	8.23	121.61	63.94	56.08	11.04	5.40	6.53	13.52	9.95

seedlings only reaches 0.6% (0.06 GJ ha^{-1}). Crop protection contributes 2.7% to the total GER (0.27 GJ ha^{-1}) and the expenditure on tools, barely 0.5% (0.05 GJ ha^{-1}). The energy associated with human labor represents 2.3% of the overall energy requirements (0.18 GJ ha^{-1}).

3.3. Efficiency Indicators and Energy Productivity

The values of the energy ratios of organic farming in Andalusia in 2005 are summarized in Table 6. Organic farming in Andalusia in 2005 was a net energy producing activity, its net energy contribution valued at 323,958 GJ. The sector's aggregate energy ratio (ER) was estimated at 1.40. This means that, in terms of energy, 1.4 output units were obtained for every input unit entering the system.

Nevertheless, not all the groups of crops produced net energy and not to the same degree. In fact, only three groups (extensive crops, olive and other fruits) yielded net energy, that is, their energy output was greater than the energy inputs considered. Thus, due to their territorial importance and the high energy content of their output, extensive crops and olives were the groups with higher net energy ratios and, consequently, the most efficient ones, their energy ratios reaching 2.86 and 2.08, respectively. The other fruits group has an energy ratio valued at 1.64. Subtropical fruits, nuts, and vine have negative NE ratios, but their energy ratios are close to 1. On the contrary, horticultural crops and citrus fruits are characterized by very low energy ratios, respectively, 0.18 and 0.39.

The energy efficiency of organic farming is 2.02 when measured according to the use of nonrenewable energy through the nonrenewable energy ratio (ERnr). If only the cost of nonrenewable energy is considered, subtropical fruits and vines, which previously had energy ratios that were lower than 1, have now nonrenewable energy ratios over 1. The nonrenewable energy ratio of nuts was close to 1 but the limited output of these crops in a low-yield agricultural year did not compensate their requirements of nonrenewable energy. In the case of horticultural crops and citrus fruits, characterized by high energy intensities, the nonrenewable energy ratio remained low, at 0.25 and 0.65, respectively, showing the high dependence on nonrenewable energies of these organic crops.

4. DISCUSSION

The first group (A) is integrated by olives, extensive crops, and nuts, which together cover 94.8% of the total area and generate 91% of the total energy. These crops are characterized by low agricultural yields, which are however compensated for with their large cultivation area and their high energy contents. Crops in group A are also among those with greater weight in

TABLE 6 Energy indicators of organic farming in Andalusia in 2005

Types of energy	Unit	Extensive crops	Horticultural crops	Citrus fruits	Subtropical fruits	Other fruits	Nuts	Olive	Vine	Weighted average
Net energy	GJ	247,785	−148,732	−48,431	−4,339	3,546	−16,952	292,719	−1,638	323,958
Energy ratio (ER)	–	2.86	0.18	0.39	0.85	1.64	0.84	2.08	0.76	1.4
Nonrenewable ER	–	5.08	0.25	0.65	1.19	1.91	0.92	3.1	1.03	2.02

the overall energy cost or gross energy requirement (62.9% of the GER). Nevertheless, these are crops with very low GER per ha (extensive crops: 8.23 GJ ha^{-1}, olive: 6.53 GJ ha^{-1}, nuts: 5.40 GJ ha^{-1}) whose main energy inputs are organic fertilization (in the case of extensive crops and olive) and agricultural mechanization.

The second group (B) is integrated by horticultural crops, subtropical fruits, and citrus fruits. This group includes crops with medium and high energy yields resulting from high agricultural yields, but with little territorial presence and, therefore, little weight in the aggregate energy output. Citrus fruits and horticultural crops are characterized by low intrinsic energy contents and high agricultural yields. With regard to subtropical fruits, the fruits, especially the avocado, have high energy contents that reinforce the energy yield of this group and compensate its medium agricultural yields. Group B includes the most productive organic crops in terms of agriculture and those that are the most export-oriented. At the same time, crops of group B are characterized by high-energy intensities related to capital-intensive management systems. Thus, horticultural crops, which only cover 1.8% of the total area, represent however 22.3% of the gross energy requirements of organic farming. This is the result of their very high GER (121.61 GJ ha^{-1}), which reflects the use of greenhouses with irrigation systems complemented with heavy fertilization and crop protection in strongly export-oriented mechanized horticultural systems. Citrus fruits and subtropical fruits are also characterized by mechanized irrigation systems with an important use of inputs that result in high—although lower than in the case of horticultural crops—energy intensities (63.94 GJ ha^{-1} and 56.08 GJ ha^{-1}, respectively).

Finally, there is a third group (C) integrated by other fruits and vines, characterized by their low intrinsic energy, very reduced cultivation area, medium-low agricultural yields resulting in their very limited weight in the aggregate energy output of organic farming and low GER per ha—but higher than those of group A—that point out, for instance, to the need of resorting to crop protection against the attack of fungus in vines, the use of irrigation in certain areas and the general use of mechanization and fertilization.

The energy performance of Andalusian organic crops is explained by the interaction of energy output and energy inputs in aggregated terms which, in turn, are determined by the cultivation area, agricultural yields, intrinsic energy content of crops, and the management system. At the same time, the management system is determined by five other factors: mechanization, fertilization, the use of irrigation, the use of greenhouses and the protection of crops through biological inputs permitted in organic farming. Table 7 summarizes these factors that, in terms of energy, characterize the different groups of crops.

Energy efficiency cannot be the only factor to take into consideration in relation to human food decisions. For example, the provision of vitamins

TABLE 7 Energy characterization of organic crops in Andalusia in 2005

	Output			Input				Energy efficiency	
Crops	Area	Energy	Agricultural yield	Mechanization	Fertilization	Irrigation	Others	ER	ERnr
Group A									
Extensive crops	high	high	low	medium	medium	very low		>1	>1
Olive	high	high	low	medium-low	medium	very low		>1	>1
Nuts	high	high	low	low	low	very low		<1	<1
Group B									
Horticultural crops	low	low	high	high	high	high	greenhouse + crop protection	<1	<1
Subtropical fruits	low	Low	high	high	high	high	crop protection	<1	>1
Citrus fruits	low	low	high	high	high	high	crop protection	<1	<1
Group C									
Other fruits	low	low	medium	medium	low	low		>1	>1
Vine	low	low	medium	medium	medium	low	crop protection	<1	>1

by vegetables and fruits is crucial for a healthy diet besides the energy component. But in a context of environmental fragility and energy shortage, energy is going to become a critical question and thus the energy balance can be interpreted as an indicator of energy sustainability and viability.

ER that are higher than 1 are concentrated in groups A and C, which are positive net energy producer crop groups. Within group A, nuts have energy balance that is however close to 1. The poor harvest of 2005 and the localization of these crops in mountain areas explain their exceptionally reduced agricultural yields. Within group C, the energy balance of other fruits is greater than 1, while that of vines is less than 1. However, when only nonrenewable energy is taken into consideration, the energy balance of vines becomes greater than 1. On the contrary, crops in group B are characterized by ER that are lower than 1 as a result of the high energy requirements of their intensive cultivation systems, linked to irrigation, heavy fertilization, crop protection and mechanization, to which, in the case of horticultural crops, the use of greenhouses needs to be added. If the energy ratio is calculated by taking into account the consumption of nonrenewable energy only (ERnr), the groups of crops with energy ratios that are lower than 1 are reduced to 3.

As a consequence, the ER of the organic farming sector in Andalusia in 2005, although higher than 1 (1.40), is relatively low in relation to the actual energy potential of organic farming as shown in numerous studies (MAAF 2000; Klimeková and Lechocká 2007; Ziesemer 2007). For instance, in relation to the group of crops with higher weight in this sector and despite the fact that the studies are not strictly comparable, Kaltsas et al. (2007) estimated the ER of organic olive at 3.2 (2.4 higher than that of conventional olive), the results being similar to the ones obtained by Guzmán Casado and Alonso Mielgo (2008) for the case of organic olive in Andalusia.

5. CONCLUSIONS

In aggregate terms, the ER of Andalusian organic farming in 2005 was estimated at 1.40, the extensive crops (2.86), horticultural crops (0.18), citrus fruits (0.39), subtropical fruits (0.85), other fruits (1.64), nuts (0.54), olive (2.08), and vine (0.76). The ER of organic farming improves and reaches 2.02 if calculated exclusively in terms of nonrenewable energy, given the important contribution of renewable energy from organic fertilization.

The explanatory factors of the energy performance of organic farming are related to the system's output and inputs. In aggregate terms, the determinant factors of the energy output are the crops' territorial distribution, which is the result of the historical productive specialization of the region, agricultural yield, and intrinsic energy contents. The determinant factors of the energy inputs show the dependence on nonrenewable energy sources of organic farming (6.88 GJ ha^{-1}). Agricultural mechanization and, consequently, the consumption of diesel and derivatives (4.40 GJ GJ ha^{-1}) and machinery (0.79 GJ ha^{-1}), as well as the consumption of electric power in irrigation systems (1.09 GJ ha^{-1}) are the three main factors determining the nonrenewable energy origin of 69.1% of the energy requirements of organic farming in Andalusia in 2005.

The relatively low energy ratio of organic farming in Andalusia shows the limitations, in terms of energy, of the present ecological management model and, as a consequence, the need to implement measures leading to greater efficiency and sustainability. These limitations allow identifying the areas of research and the technical changes that require further work and implementation with the purpose of increasing the energy gains of organic farming. The main energy limitation, on the side of the output, is due to the low agricultural yields of certain crops, a fact that suggests the reinforcement of applied agronomic research with agroecological approaches. The limitations on the side of the inputs are: 1) agricultural mechanization and the subsequent high consumption of diesel and oil derivatives such as lubricants; 2) irrigation and the subsequent high consumption of electric power for water pumping; 3) the cultivation of vegetables in greenhouses and the subsequent high consumption of electric power, materials (plastics), and industrial biological inputs. The energy challenge on the side of the inputs is double. On the one hand, the need is to reduce the gross energy requirements without compromising agricultural yields. On the other hand, the requisite is to substitute nonrenewable energy sources with renewable energy sources.

NOMENCLATURE

CE	capital energy
CEnr	nonrenewable capital energy
DE	direct energy
DEnr	nonrenewable direct energy
EO	energy output
EP	energy productivity
ER	energy ratio
ERnr	nonrenewable energy ratio
GE	gross energy
GER	gross energy requirements
GERnr	nonrenewable gross energy requirements
IE	indirect energy
IEnr	nonrenewable indirect energy
NE	net energy

NOTES

1. Another important research line within energy analysis has been the study of agro-fuels and their viability (Pimentel and Patzek 2005; Pradhan et al. 2008; García et al. 2011; Pleanjai and Gheewala 2009).

2. Research project financed by the Department of Agriculture of the Andalusian Regional Government (Soler et al. 2009; see also previous work Pérez-Neira 2010).

3. This is the sum of the direct and indirect energy of the diesel, lubricants and plastics consumed in the farm during 2005.

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