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Rainfed crop energy balance of different farming systems and crop rotations in a semi-arid environment: Results of a long-term trial

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ABSTRACT

This study was conducted to determine how energy balances of crop production are affected by three farming systems (conventional, conservation with no tillage, and organic) and four barley-based crop rotations (barley followed by fallow [B–F], barley in rotation with vetch [B–V] or sunflower [B–S], and barley monoculture [B–B]), under the semi-arid conditions of central Spain over a 15-year period (1993/94–2007/08). As inputs, the factors supplied and controlled by farmers were considered. The energy balance variables considered were net energy produced (energy output minus energy input), the energy output/input ratio, and energy productivity (crop yield per unit energy input). The total energy inputs were 3.0–3.5 times greater in the conservation (10.4 GJ ha^{-1} year^{-1}) and conventional (11.7 GJ ha^{-1} year^{-1}) systems than in the organic system (3.41 GJ ha^{-1} year^{-1}). With respect to the crop rotations, the total energy inputs varied from 6.19 GJ ha^{-1} year^{-1} for B–F to 11.7 GJ ha^{-1} year^{-1} for B–B. The lowest energy use corresponded to B–F in the organic system (2.56 GJ ha^{-1} year^{-1}), and the highest to B–B in the conventional and conservation systems (16.3 and 14.9 GJ ha^{-1} year^{-1}, respectively). Energy output was lowest in the organic system (17.9 GJ ha^{-1} year^{-1}), a consequence of the lower barley grain and vetch hay yields. With respect to the crop rotation, the order followed B–B (19.1 GJ ha^{-1} year^{-1}) $\approx$ B–F $<$ B–S $<$ B–V (29.3 GJ ha^{-1} year^{-1}, 53% higher). All the energy efficiency variables analysed had the highest values for the organic system (net energy of 14.5 GJ ha^{-1} year^{-1}, output/input ratio of 5.36 and energy productivity of 400 kg GJ^{-1}). No differences were recorded between the conventional and conservation managements. This indicates that, in terms of energy efficiency, the viability of organic systems (low-input practices) under semi-arid conditions, compared to farming systems requiring agrochemicals (conventional and conservation), would appear more recommendable. Cereal monoculture (B–B), independent of the crop management employed, is an energetically unfavourable practice, especially in the driest seasons. However, crop rotations, especially those including a leguminous plant, increase energy efficiency.

1. Introduction

Energy balances for agricultural systems have been studied since the 1970s (Pimentel et al., 1973; Berardi, 1978). Researchers have performed detailed energy balances for different crops and farm management systems all over the world in attempts to assess the efficiency and environmental impact of production systems (Campiglia et al., 2007; Akpinar et al., 2009). Energy balances provide an important view of the agriculture as a user and producer of energy (Risoud, 2000).

In the economic sense, the aim of any agricultural practice is to achieve maximum profit. However, the viability of a production system does not depend solely on crop yield, but also on its efficiency in the use of available resources. In developed countries, the economic profitability of different productive systems is currently obfuscated by the granting of subsidies of diverse origin that affect both production factors (or inputs) and the final product (or output). Leaving such external aid aside, energy balances should reveal the most efficient, and therefore the most advisable, form of management for each agroclimatic region. In this context, conducting energy balances can lead to more efficient and environment-friendly production systems (Gündoğmuş, 2006).

In recent years the relationship between agriculture and the environment has changed, and concerns regarding the sustainability of agricultural production systems have come to the fore. This has led to tension between "production vs. conservation".

Abbreviations: B–F, barley–fallow; B–V, barley–vetch; B–S, barley–sunflower; B–B, barley monoculture.

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Conservation systems are understood as sustainable production systems, while production first oriented practices imply production should take place, without considering the environmental and energetic effects. Conservation practices, however, balance environmental and energetic effects with production. As a consequence, farmers are now continuously requested to increase crop yields while at the same time preserving the environment by reducing the dependency of agriculture on external, non-renewable fossil energy and reducing the emission of greenhouse gases (Bailey et al., 2003; Bechini and Castoldi, 2009). To achieve these goals, solutions such as developing integrated arable farming systems, conservation tillage practices, and low-input or organic farming have been proposed (Edwards, 1987; Hernanz et al., 1995; Vereijken, 1997; Pervanchon et al., 2002). In general, integrated farming systems involve lower inputs of fertilizer and pesticides, and fewer tillage operations (Edwards, 1987). Conservation agriculture promotes minimal disturbance of the soil (minimum or no tillage), the balanced application of chemical inputs, and the careful management of residues and wastes (Dumanski et al., 2006). This type of system, however, often requires increased pesticide use. Organic or ecological farming is based on the banning of synthetic biocides and fertilizers (Helander and Delin, 2004; Jørgensen et al., 2005), and promotes the use of renewable resources in production and processing systems to prevent pollution and avoid waste (IFOAM, 2002).

In Spain, the energetic and environmental aims for the agricultural sector of the country's Action Plan for Saving Energy and Energy Efficiency 2008–2012 are to save 1634 ktep[1] of primary energy (oil 47.6%, coal 14.4%, nuclear fuel 9.7%, natural gas 21.8%, renewable resources 6.5%) and to achieve a 5112 ktep reduction in CO_2 emissions (the latter representing a €92 million profit). This Action Plan recognizes energy saving and energy efficiency as an instrument of economic growth and social well-being, and promulgates the importance of these concepts in all associated National Strategies, especially in those relative to climate change (IDAE, 2007).

Energy inputs and outputs are important factors affecting the energy efficiency and environmental impact of crop production. The magnitude of these factors, and consequently the energy efficiency of an agrarian system, varies considerably depending on farm location (weather, soil type), crop rotations, the use of fertilizers, etc. (Bonny, 1993; Rathke et al., 2007). This shows the importance of determining energy balances for all pedo-climatic conditions (Pacini et al., 2003).

The efficiency of energy use can be increased by reducing inputs such as fertilizer and tillage operations, or by increasing outputs such as crop yields (Swanton et al., 1996). In some cases, a reduction in energy inputs entails a proportional reduction in crop yield. In such cases energy efficiency is not significantly affected (Risoud, 2000; Bailey et al., 2003). In some modern, high-input farming systems, crop yields have improved continuously as a result of increasing inputs of agrochemicals (inputs of fossil energy) and the growth of more productive cultivars (Hülsbergen et al., 2001). Other studies report reductions in energy efficiency due to energy inputs increasing faster than energy outputs, the result of a growing dependency on inorganic, non-renewable resources (Weseen and Lindenbach, 1998; Gündoğmuş, 2006; Gündoğmuş and Bayramoğlu, 2006).

This study has attempted to achieve greater sustainability of agricultural systems, whatever the production system employed, and to get sustainable and profitable production for the farmer with a minimal energy and environmental damage over time. Under this general assumption, the aim of the present work was to assess the effects of conventional, conservation and organic systems and different barley-based crop rotations (barley monoculture and in rotation with vetch, sunflower and fallow) on the energy balance of crop production under the semi-arid conditions over a 15-year period (1993/94–2007/08). As proposed by Rathke et al. (2007), these production systems were compared under the same site conditions and using the same methods for calculating the energy balance values, which permits a valid comparison among treatments.

2. Materials and methods

2.1. Research site

Field experiments were conducted from 1993/94 to 2007/08 at the La Higueruela Experimental Farm (4°26′W, 40°04′N, altitude 450 m) (property of the Spanish National Research Council), Santa Olalla, Toledo, in the semi-arid region of Castilla-La Mancha, central Spain. The climate of the study area is semi-arid Mediterranean, with a four month drought period in summer coinciding with the highest temperatures. The average seasonal (1 September–31 August) rainfall during the experimental period was 480 mm, irregularly distributed intra- and inter-annually in timing and amount. The highest rainfalls were recorded in 1997/98, 2000/01 and 2006/07 (637, 649 and 619 mm, respectively), and the lowest in 1994/95, 1998/99 and 2004/05 (275, 292 and 282 mm, respectively). The average annual temperature was 15.3 °C (winter, 8.4 °C; spring, 17.9 °C; summer, 24.1 °C; autumn, 10.7 °C). The soil at the experimental site is classified as a Vertisol, Chromic Calcixererts (USDA, 2006). Physical and chemical characteristics of the soil at different depths at the beginning of the experiments (November 1993) are presented in Table 1.

Agriculture in the study region is generally rainfed, cereal-based and extensively managed, with low crop yields due to the low and especially fluctuating rainfall, high summer temperatures, high solar radiation, high evapotranspiration, and consequently, poor fertility of the soils.

2.2. Field experiment

Experiments were conducted in a split-plot randomized complete block design with farming system as main plots and crop rotation as subplots, replicated thee times. Farming systems included conventional management, conservation management with no tillage, and organic farming. Conventional management involved the use of a mouldboard plough for tillage, chemical fertilizers and herbicides. Conservation management involved zero tillage, direct sowing and the use of chemical fertilizers and herbicides (Spanish RD 2352/2004). Organic farming involved the use of a cultivator and a disc harrow for tillage and no chemical

Table 1
Initial soil physical and chemical characteristics (year 1993) of the experimental plot.

Soil parameter	Depth (cm)			
	0–25	25–40	40–90	90–120
pH (1:2.5 soil:water)	7.8	7.9	8.1	8.2
EC (1:5 soil:water) (dS m^{-1})	0.18	0.24	0.21	0.40
Organic matter (Walkley–Black) (%)	1.35	0.70	0.70	0.40
Total organic carbon (Walkley–Black) (%)	0.78	0.41	0.41	0.23
Sand (2–0.05 mm) (%)	13.7	12.9	12.9	13.6
Silt (0.05–0.002 mm) (%)	26.3	26.6	28.5	29.3
Clay (<0.002 mm) (%)	60.0	60.5	58.6	57.1
Structure	Crumb	Polyhedral angular	Prismatic	Angular blocky

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[1] 1 tep = equivalent petroleum tonne (41.84×10^9 J).

fertilizers or herbicides (EC 834/2007). Subplot treatments were four barley-based crop rotations, all two years in length: barley–fallow (B–F), barley–vetch (B–V), barley–sunflower (B–S) and barley monoculture (B–B). Although monoculture is not considered an organic practice, it was included as such to compare the behaviour of crops under such management. The rotations were simultaneously duplicated to have all phases of each rotation present every year, and they were cycled on their assigned plots. Subplot size was 800 m^2 (40 m × 20 m).

The cultivation practices followed were similar to those employed by local growers, adapted to the type of soil and weed incidence, etc., and remained constant for each farming system and rotation during the entire experiment. Table 2 shows all the fieldwork undertaken, and amounts of fertilizers, seeds and fuel used in each treatment. The depth of tillage was 25 cm for mouldboard plough, 20 cm for cultivator and 5 cm for disc harrow. Tillage operations were performed in autumn for barley crops and in spring and summer for fallow. In the conventional and conservation systems, chemical fertilizers were applied in the same quantity at barley pre-sowing in a mixed form (8–15–15 N–P–K), and as a top-dressing at the tillering stage in the form of calcium ammonium nitrate (30% N), at an average total rate of 90–60–60 kg N–P–K ha^{-1} (estimated from the average crop extractions and the yield crops in this area). Sunflower and vetch crops were fertilized at pre-sowing with the same mixed form but at a lower rate (16–30–30 kg N–P–K ha^{-1}) (Table 2). In conventional system, fertilizers were incorporated by cultivator. In the conservation system, the use of machinery (and therefore of fuel) was lower than in the conventional system, but the supply of herbicides was greater due to additional applications of glyphosate. In the organic farming system, the fertilization of the different crop rotations only involved the N provided by the vetch crop in B-V and the barley straw in all rotations.

Crop yields were assessed for an area of approximately 300 m^2; subplot perimeters were avoided to prevent the effects of interference among treatments. The barley and sunflower crops were combine-harvested after reaching physiological maturity, usually in early July and September respectively. The vetch crop was harvested using a cutter bar at the flowering stage in April-May and used for hay production. The yields recorded referred to 12% moisture content for grain barley and sunflower. Crops residues were uniformly distributed to the same plots where they were produced at the end of the crop season. This practice is not always followed in conventional and conservation farming systems but is required in organic farming. This was performed over the entire experimental period and for all treatments to avoid introducing a source of variation.

2.3. Energy balance

The energy balances were determined as reported by Hülsbergen et al. (2001). This requires the identification of the inputs and the outputs involved and their conversion to energy values by means of corresponding energy coefficients or equivalents (Table 3). It should be noted that there is a great variation in the energy equivalents reported in the literature, the result of differences in the methods of calculation and in the spatial and temporal system boundaries used (Hülsbergen et al., 2001). This impedes making comparisons of energy balances among studies performed with different methodologies.

In relation to energy inputs and according with previous studies, only the involved factors supplied and controlled by farmers have been included, although no-control factors, source of nutrient (dust, rainfall, organic matter, etc.) may be present. Thus, in agreement with Hülsbergen et al. (2001) and Rathke et al. (2007), solar energy was not considered because its incorporation

Table 2
Summary of the operations performed for each farming system and crop rotation.[a]

Field operation	Conventional farming							Conservation (no-tillage) farming							Organic farming						
	B–F[b]		B–V[c]		B–S[d]		B–B[e]	B–F		B–V		B–S		B–B	B–F		B–V		B–S		B–B
	B	F	B	V	B	S	B	B	F	B	V	B	S	B	B	F	B	V	B	S	B
Machinery (number of operations)																					
Mouldboard plough	1	–	1	1	1	1	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Cultivator	2	1	2	2	2	2	2	–	–	–	–	–	–	–	1	4	2	2	2	3	2
Disc harrow	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	1	1	1	1	1
Spreader	2	–	2	1	2	1	2	2	–	2	1	2	1	2	–	–	–	–	–	–	–
Conventional sower	1	–	1	1	1	1	1	–	–	–	–	–	–	–	1	–	1	1	1	1	1
Direct sower	–	–	–	–	–	–	–	1	–	1	1	1	1	1	–	–	–	–	–	–	–
Sprayer	1	–	1	–	1	1	1	2	2	2	1	2	2	2	–	–	–	–	–	–	–
Harvester	1	–	1	–	1	1	1	1	–	1	–	1	1	1	1	–	1	–	1	1	1
Cutter bar	–	–	–	1	–	–	–	–	–	–	1	–	–	–	–	–	–	1	–	–	–
Rake	–	–	–	1	–	–	–	–	–	–	1	–	–	–	–	–	–	1	–	–	–
Baler	–	–	–	1	–	–	–	–	–	–	1	–	–	–	–	–	–	1	–	–	–
Fuel (l)[f]	34.5	4.0	34.5	36.0	34.5	33.8	69.0	16.5	2.0	16.5	18.0	16.5	15.8	33.0	19.5	16.0	23.5	26.8	23.5	27.5	47.0
Fertilizer (kg)																					
8–15–15 (N–P–K)	200	–	200	100	200	200	400	200	–	200	100	200	200	400	–	–	–	–	–	–	–
Calc. amm. nitr. (30% N)	100	–	100	–	100	100	200	100	–	100	–	100	100	200	–	–	–	–	–	–	–
Seed (kg)	65	–	65	50	65	1.5	130	65	–	65	50	65	1.5	130	65	–	65	50	65	1.5	130
Herbicide (l)																					
Glyphosate	–	–	–	–	–	–	–	0.75	1.75	0.75	0.75	0.75	0.75	1.5	–	–	–	–	–	–	–
Various (postemergence)	1	–	1	–	1	1	2	1	–	1	–	1	1	2	–	–	–	–	–	–	–

[a] Data correspond to one hectare and year for a complete crop rotation. Thus, data in columns B, F, V, S for rotations B–F, B–V, B–S, correspond to half a hectare; data in B–B column correspond to one hectare.

[b] Barley–fallow rotation.

[c] Barley–vetch rotation.

[d] Barley–sunflower rotation.

[e] Continuous barley.

[f] Consumption accumulated by field operations.

Table 3
Energy coefficients for different input and output values, and fuel consumption, for all field operations.

Item	Energy coefficients	Fuel consumption[f]
Fuel	MJ l^{-1}	
Diesel[a]	41.8	
Machinery (including implement and tractor)[b]	MJ ha^{-1}	l ha^{-1}
Mouldboard plough	67.6	26.0
Cultivator	17.4	8.0
Disc harrow	44.8	9.0
Spreader	3.7	1.5
Conventional sower	28.4	7.0
Direct sower	54.6	11.0
Sprayer	3.5	2.0
Harvester	83.9	15.0
Cutter bar	21.7	7.5
Rake	8.4	4.0
Baler	37.7	10.0
Fertilizers	MJ kg^{-1}	
8-15-15 (N-P-K)[a]	9.88	
Calcium ammonium nitrate (30% N)[c]	35.3	
Herbicides[b]	MJ l^{-1}	
Glyphosate (20%)	90.0	
Various (postemergence)	140.0	
Products	MJ kg^{-1}	
Barley seed/grain[d,e]	14.6	
Vetch seed[b]	10.0	
Vetch hay[b]	9.0	
Sunflower seed/grain[a,e]	13.0	

[a] Pimentel and Patzek (2005).
[b] Hernanz et al. (1995).
[c] Hülsbergen et al. (2001).
[d] Pimentel (1980).
[e] Seeds obtained in the own farm (energy for processing, storage, and sale, not considered).
[f] Boto et al. (2005).

would mask variations in the input of fossil energy related to the different treatments. Energy removed from the soil in the form of plant nutrients nor for energy captured in terms of soil organic matter increases or losses were not considered in the energy balance (Zentner et al., 1998, 2004; Rathke et al., 2007), due to the great fluctuations in soil organic matter throughout the study period. It was as result of the erratic rainfall distribution, which favoured in some cases the soil organic matter accumulation, especially in the conservation system due to the lower soil aeration, but, however, increased the organic matter mineralization rate when the weather (temperature and humidity) conditions were appropriated (data not shown).

The calculation of energy inputs was based on estimating the total direct (fuel) and indirect energy factors (energy used in producing machines, fertilizers, herbicides and seeds) involved, but not including those unrelated to production (e.g., energy used in processing, storage, transport and the sale of outputs), as in previous reports (Zentner et al., 1989, 2004; Rathke et al., 2007). The direct energy input (MJ ha^{-1}) was estimated from the amount of fuel (diesel) consumed in each type of field work (l ha^{-1}), depending on the number of operations performed and the machinery employed (Table 2), and considering a conversion factor of 41.8 MJ l^{-1} (Pimentel and Patzek, 2005) (Table 3). Indirect energy inputs were determined by taking into account the energy required for manufacturing the machinery and raw materials employed, as well as that involved in seed, fertilizer and herbicide manufacture, packaging and delivery (Bailey et al., 2003). These inputs were calculated from the amount of product used in each rotation and farming system (kg ha^{-1}, l ha^{-1}; Table 2) and the corresponding energy equivalents (MJ kg^{-1}, MJ l^{-1}; Table 3). In relation to barley and sunflower seeds, on having been obtained in the own farm (no suffering any additional manipulation), the corresponding grain energetic coefficient was used (Table 3). Human labour was not included, since only represents a very small amount of the total energy input (12.2, 6.8 and 9.0 MJ ha^{-1} $year^{-1}$ in conventional, conservation and organic farming systems, respectively, representing 0.1, 0.06 and 0.2% of total energy inputs in each system), values of a technified agriculture in developed countries (Zentner et al., 1984, 2004; Borin et al., 1997; Hülsbergen et al., 2001; Rathke et al., 2007). However, in situations or practices that require a significant use of human labour, this input should be included.

The energy output for each crop rotation was considered as the calorific value of the harvested main product (barley and sunflower grain, vetch hay) (Hülsbergen et al., 2001). This was calculated based on the total yield (kg ha^{-1}) and its corresponding energy coefficient (Table 3), estimated at 14.6 MJ kg^{-1} for barley grain (Pimentel, 1980), 9.0 MJ kg^{-1} for vetch hay (Hernanz et al., 1995), and 13.0 MJ kg^{-1} for sunflower seed (Pimentel and Patzek, 2005). Crop residues were not considered in the energy balance since they were returned to the land at the end of the crop season, although they could be sequestered differently by different systems, especially depending on the weather conditions.

The energy efficiency variables contemplated (described in Table 4) were (i) net energy produced (NE) (also known as energy gain or energy balance), (ii) the energy output/input ratio (O/I), and (iii) energy productivity (EP).

2.4. Statistical analysis

Before the statistical analysis was conducted, all variables were checked to make sure they fitted properly to a normal distribution. Data corresponding to the period 1993/94–2007/08 ($n = 512$) were analysed using the split-plot procedure considering the factors farming system, rotation, year and replication as variables of classification. The dependent variables (yield, energy output, net energy produced, energy output/input ratio, energy productivity) were subjected to analysis of variance (ANOVA). Duncan's multiple range test ($P < 0.05$) was used to analyse significant results (InfoStat 2006d.2). All results were expressed with respect to one hectare and year for a complete rotation-farming system, distinguishing within rotations the corresponding crops (barley, vetch, sunflower). In the B–F rotation, the energy used in fallowing was included as an input in the following barley crop. When the different farming systems and crop rotations were analysed independently, a statistical model with the block nested within the factor 'year' was contemplated. Energy inputs were not analysed statistically since they cannot be considered random variables to be constant for each rotation and farming system in every season.

Table 4
Definition of energy variables.

Variable	Definition	Unit
Direct energy input (Ed)	Input for diesel	GJ ha^{-1} $year^{-1}$
Indirect energy input (Ei)	Machines + fertilizers + herbicides + seeds	GJ ha^{-1} $year^{-1}$
Total energy input (EI)	EI = Ed + Ei	GJ ha^{-1} $year^{-1}$
Energy output (EO)	Energy in the harvested biomass (main product)	GJ ha^{-1} $year^{-1}$
Net energy (NE)	NE = EI − EO	GJ ha^{-1} $year^{-1}$
Output/input ratio (O/I)	O/I = EO/EI	
Energy productivity (EP)	EP = Crop yield/EI	kg GJ^{-1}

Source: Hülsbergen et al. (2001), Gezer et al. (2003) and Rathke et al. (2007).

Table 5
Summary of the analysis of variance (ANOVA) for energy variables over the 15-year experiment.

Energy variable	Source of variation					
	Farming system (FS)		Crop rotation (CR)		FS × CR	
	MS	*F*	MS	*F*	MS	*F*
Energy output	3145	14.03**	3030	347.01**	88	10.09**
Net energy	9744	3.10*	4213	482.49**	57	6.48**
Output/input ratio	539	56.32**	127	425.85**	14	45.72**
Energy productivity	3,009,753	55.32**	1,135,202	743.88**	110,101	72.15**

MS: mean square. *F*: *F*-statistic.
[*] Significant at $P < 0.05$.
[**] Significant at $P < 0.01$.

3. Results

Differences in crop yields were seen among years and, consequently, in energy output and the energy efficiency variables analysed. These differences were the result of variation in the weather conditions, which indicates the importance of long-term studies in these experiments. Yields were noticeably lower when precipitation was below normal or irregularly distributed throughout the season, as reported by other authors (Rathke et al., 2007).

The analysis of variance (ANOVA) for the energy output and energy efficiency variables considered is summarized in Table 5. All interactions of year with treatments (system, rotation) were significant. To facilitate and simplify the comprehension of the results, the year-to-year data are not shown; rather, data across 15 years are provided.

3.1. Energy inputs

Averaged across years and crop sequences (Table 6), total energy inputs were 3.0 and 3.5 times higher in the conservation (10.4 GJ ha^{-1} year^{-1}) and conventional (11.7 GJ ha^{-1} year^{-1}) systems than in organic farming (3.41 GJ ha^{-1} year^{-1}). Direct energy use ranged from 12% of the total energy inputs in the conservation system to 56% in the organic system. With respect to indirect energy inputs, fertilizer made the highest contribution to total energy input in the conventional and conservation treatments (63 and 71%, respectively), whereas seed was the most important in organic farming (39%). The total energy requirement was slightly higher in the conventional than in the conservation system, the result of the greater use of machinery and, consequently, of fuel, even though the use of herbicides was slightly lowers. Fuel consumption was maximum in the conventional system (2.57 GJ ha^{-1} year^{-1}), followed by organic farming (1.92 GJ ha^{-1} year^{-1}) and the conservation system (1.24 GJ ha^{-1} year^{-1}). Herbicides only represented 1.8 and 3.5% of the total energy requirements in the conventional and conservation systems, respectively. The lowest figures were for machinery, ranging from 1.2 to 1.7% for both the conservation and conventional systems, to 5% in organic farming. With respect to crop rotation, total energy varied from 6.19 GJ ha^{-1} year^{-1} for B–F to 11.7 GJ ha^{-1} year^{-1} for B–B (Table 7). This indicates that the energy requirements of barley monoculture (B–B) are almost double those when a fallow period is included in the rotation (B–F). It is also higher than the values reached when different crops are included in the crop sequences. Direct inputs ranged from 18% in B–B to 27% in B–S. In relation to indirect inputs, fertilizer was the main energy input, accounting for 52% in B–V and 62% in B–B. This was followed by seeds, representing about 12–17% in all the crop sequences contemplated. Table 8 shows the highest total energy input was that corresponding to B–B in the conventional and conservation systems (16.3 and 14.9 GJ ha^{-1} year^{-1}, respectively), while the lowest energy requirements were recorded for organic farming, with very similar values for all four rotations (between 2.56 GJ ha^{-1} in B–F and 4.05 in B–B). The table also shows that barley required the highest energy inputs, especially in the B–B rotation in the conventional and conservation systems, while sunflower was the least energy-consuming crop.

Energy input was more influenced by farming system than by crop sequence, as indicated by the ratios between the most and the

Table 6
Effect of farming system on energy variables for the complete cropping sequence over the 15-year experiment.

Energy variable	Conventional farming	Conservation (no tillage) farming	Organic farming
Energy input (GJ ha^{-1} year^{-1})			
Direct (Ed) (fuel)	2.57	1.24	1.92
Indirect (Ei)			
Machinery	0.20	0.13	0.17
Seeds	1.32	1.32	1.32
Herbicides	0.21	0.37	0
Fertilizer	7.38	7.38	0
Total Ei	9.11	9.20	1.49
Total energy input (Ed + Ei)	11.7 (100)	10.4 (90)	3.41 (29)
Energy output (GJ ha^{-1} year^{-1})	25.7 a (100)	23.4 a (90)	17.9 b (69)
Net energy (GJ ha^{-1} year^{-1})	14.0 ab	13.0 b	14.5 a
Output/input ratio	2.35 b	2.38 b	5.36 a
Energy productivity (kg GJ^{-1})	173 b	177 b	400 a

Means in the same row followed by the same letter do not differ at $P < 0.05$. Figures in parentheses indicate percentage compared to conventional farming.

Table 7
Effect of crop rotation on energy variables for the complete crop sequence over the 15-year experiment.

Energy variable	B–F[a]	B–V[b]	B–S[c]	B–B[d]
Energy Input (GJ ha^{-1} year^{-1})				
Direct (fuel)	1.29	2.16	2.11	2.08
Indirect				
Machinery	0.11	0.18	0.19	0.19
Seeds	0.95	1.45	0.97	1.90
Herbicides	0.17	0.14	0.23	0.23
Fertilizer	3.67	4.33	4.33	7.34
Subtotal	4.90	6.10	5.72	9.66
Total energy input	6.19	8.26	7.83	11.7
Energy output (GJ ha^{-1} year^{-1})	19.4 c	29.3 a	22.0 b	19.1 c
Net energy (GJ ha^{-1} year^{-1})	13.2 b	21.0 a	14.1 b	7.41 c
Output/input ratio	3.85 b	4.23 a	3.38 c	2.00 d
Energy productivity (kg GJ^{-1})	263 b	360 a	239 c	137 d

Means in the same row followed by the same letter do not differ at $P < 0.05$. Figures in parentheses indicate percentage compared to continuous barley rotation.
[a] Barley–fallow rotation.
[b] Barley–vetch rotation.
[c] Barley–sunflower rotation.
[d] Continuous barley.

Table 8
Effect of farming system and crop rotation on yield and energy variables over the 15-year experiment.

Variable	Conventional farming				Conservation (no tillage) farming				Organic farming			
	B–F[a]	B–V[b]	B–S[c]	B–B[d]	B–F	B–V	B–S	B–B	B–F	B–V	B–S	B–B
Yield (kg ha^{-1} year^{-1})												
Barley	1592 a	1394 bc	1313 bc	1642 a	1297 bc	1262 c	1334 bc	1418 b	1098 d	1021 d	853 e	874 e
Vetch hay	–	1351 a	–	–	–	1336 a	–	–	–	1116 b	–	–
Sunflower	–	–	392 a	–	–	–	348 b	–	–	–	398 a	–
Energy input (GJ ha^{-1} year^{-1})												
Barley	8.33	8.15	8.15	16.3	7.67	7.43	7.43	14.9	2.56	2.03	2.03	4.05
Vetch hay	–	3.09	–	–	–	2.37	–	–	–	1.71	–	–
Sunflower	–	–	2.67	–	–	–	1.95	–	–	–	1.27	–
Total	8.33	11.2	10.8	16.3	7.67	9.80	9.38	14.9	2.56	3.73	3.30	4.05
Energy output (GJ ha^{-1} year^{-1})												
Barley	23.3 a	20.3 bc	19.2 bc	24.0 a	18.9 bc	18.4 c	19.5 bc	20.7 b	16.0 d	14.9 d	12.5 e	12.8 e
Vetch hay	–	12.2 a	–	–	–	12.0 a	–	–	–	10.0 b	–	–
Sunflower	–	–	5.10 a	–	–	–	4.53 b	–	–	–	5.18 a	–
Total	23.3 c	32.5 a	24.3 c	24.0 c	18.9 de	30.4 b	24.0 c	20.7 d	16.0 f	24.9 c	17.7 ef	12.8 g
Net energy (GJ ha^{-1} year^{-1})												
Barley	14.9 a	12.2 bcd	11.0 cd	7.67 fg	11.3 cd	11.0 cd	12.0 bcd	5.84 g	13.5 ab	12.9 bc	10.4 de	8.72 ef
Vetch hay	–	9.07 a	–	–	–	9.65 a	–	–	–	8.33 b	–	–
Sunflower	–	–	2.43 b	–	–	–	2.58 b	–	–	–	3.91 a	–
Total	14.9 b	21.3 a	13.4 b	7.67 de	11.3 c	20.6 a	14.6 b	5.84 e	13.5 b	21.2 a	14.3 b	8.72 d
Output/input ratio												
Barley	2.79 cd	2.50 d	2.35 d	1.47 e	2.47 d	2.48 d	2.62 d	1.39 e	6.28 b	7.36 a	6.15 b	3.15 c
Vetch hay	–	3.93 c	–	–	–	5.07 b	–	–	–	5.89 a	–	–
Sunflower	–	–	1.91 c	–	–	–	2.32 b	–	–	–	4.06 a	–
Total	2.79 e	2.89 de	2.24 g	1.47 h	2.47 fg	3.11 d	2.56 ef	1.39 h	6.28 b	6.68 a	5.34 c	3.15 d
Energy productivity (kg GJ^{-1})												
Barley	191 cd	171 d	161 d	101 e	169 d	170 d	179 d	95.4 e	430 b	504 a	421 b	216 c
Vetch hay	–	436 c		–	–	563 b	–	–	–	654 a	–	–
Sunflower	–	–	147 c	–	–	–	179 b	–	–	–	313 a	–
Total	191 f	244 d	158 g	101 h	169 fg	265 d	179 fg	95.4 h	430 b	572 a	379 c	216 e

Means in the same row followed by the same letter do not differ at $P < 0.05$.
[a] Barley–fallow rotation.
[b] Barley–vetch rotation.
[c] Barley–sunflower rotation.
[d] Continuous barley.

least energy-consuming farming systems and crop rotations (3.4 in conventional vs. organic and 1.9 in B–B vs. B–F).

3.2. *Energy output*

Averaged over years and crop sequences (Table 6), the mean energy output was significantly lower for the organic system (17.9 GJ ha^{-1} year^{-1}) than for either the conventional or conservation systems (25.7 and 23.4 GJ ha^{-1} year^{-1}, respectively), a result of the lower barley grain (35 and 28% less, respectively) and vetch hay (16% less) yields. The sunflower yield was, however, largest in the organic and conventional systems ($P < 0.05$) (Table 8). The mean energy output in the conservation system was about 10% lower than in the conventional system due to reductions in crop yields, especially in barley grain (more marked in B–F) and sunflower grain yields.

Energy output increased significantly in the order B–B (19.1 GJ ha^{-1} year^{-1}) ≈ B–F < B–S (15% higher) < B–V (29.3 GJ ha^{-1} year^{-1}, 53% higher) (Table 7). It is important to note that yields of the individual crops in the crop rotations (barley grain, vetch hay and sunflower grain in B–F, B–V and B–S, respectively) were obtained for only half of the experimental plot (or every two years), whereas for continuous barley (B–B) the whole plot was cultivated (or a yield obtained each year) (see Section 2). Table 8 shows the highest energy outputs were associated with the B–V rotation regardless of the farming system, while the lowest was associated with B–B in organic farming. With respect to individual crops, the highest energy outputs were recorded for barley in all cases (higher both yields and yield energy coefficients), followed by vetch and sunflower. In the conventional and conservation systems, the barley energy outputs were similar in both the B–F and B–B rotations; in organic farming, however, this energy variable was significantly higher in the B–F than in the B–B rotation, indicating the low productivity of continuous barley when grown under organic management (874 kg ha^{-1}) (Table 8).

Over the 15-year period of the trial, the highest energy outputs were recorded in the seasons 1999/00 for the conservation system (43.3 GJ ha^{-1} year^{-1}), 2001/02 for conventional (40.8 GJ ha^{-1} year^{-1}) and 1995/96 for organic (30.3 GJ ha^{-1} year^{-1}) systems. For all three farming managements, the lowest energy outputs occurred in 1994/95, ranging from 2.21 GJ ha^{-1} year^{-1} for the conventional system to 4.87 GJ ha^{-1} year^{-1} for organic farming, a result of the lack of rainfall (data not shown). It is importance to notice that, in the driest seasons, the highest energy outputs were obtained in the organic system and in the B–F rotation.

3.3. *Energy use efficiency*

Averaged across years and crop rotations, the highest net energy value was obtained with the organic farming system (14.5 GJ ha^{-1} year^{-1}), and the lowest with the conservation system (13.0 GJ ha^{-1} year^{-1}, or 11% less; $P < 0.05$) (Table 6). With respect to the rotations, B–V produced the highest net energy (21.0 GJ ha^{-1} year^{-1}), while B–B was associated with the lowest (7.41 GJ ha^{-1} year^{-1}, or 65% less) (Table 7). Table 8 shows that the net energy was the largest for B–V in both the organic and conventional (21.3 GJ ha^{-1} year^{-1}) systems, and lowest in the B–B rotation for both the conservation (5.84 GJ ha^{-1} $year^{-1}$) and conventional (7.67 GJ ha^{-1} $year^{-1}$) systems. Barley was the crop that contributed much to the total net energy in the three systems, followed by hay vetch (Table 8). Over the 15-year period of the trial, the highest net energies were reached in the season 1999/00 for the conservation system (32.9 GJ ha^{-1} $year^{-1}$), in 2001/02 for the conventional system (29.1 GJ ha^{-1} $year^{-1}$), and in 1995/96 for the organic system (26.8 GJ ha^{-1} $year^{-1}$). In a trend similar to that of energy output, the lowest figures for all three systems occurred in 1994/95, ranging from −9.46 GJ ha^{-1} $year^{-1}$ for the conventional system to 1.46 GJ ha^{-1} $year^{-1}$ for organic farming. The net energy was negative for both the conventional and conservation systems, especially in B–B, in the driest seasons (1994/95, 1998/99 and 2004/05), and in 2000/01, season with the driest spring but the highest autumn and winter rainfall (which caused root asphyxia in barley plants). However, no negative mean energy balance was seen in any year for the organic system, even for barley monoculture (B–B) (data not shown).

As determined by the output/input ratio, organic farming appeared to be about 2.3 times more energetically efficient (5.36) than either the conventional or conservation systems (2.35 and 2.38, respectively) (Table 6). With respect to the crop rotations (Table 7), the output/input ratio rank order was B–V (4.23) > B–F (3.85) > B–S (3.38) > B–B (2.00), indicating the low energy use efficiency of barley monoculture compared to the inclusion of fallow or of alternating the cereal with other crops, especially vetch. The B–V rotation in organic farming was the most efficient (6.68), whereas the lowest ratios were obtained with B–B in both the conservation (1.39) and conventional (1.47) systems (Table 8). All the rotations in organic system were energetically more than twice as efficient as the other two systems, even for B–B. Barley was the most efficient crop in organic farming (7.36 in B–V), while vetch was the most efficient in both the conservation (5.07) and conventional (3.93) systems. Sunflower was the least energy efficient crop in all cases (data not shown). Considering the individual seasons, the highest energy output/input ratio resulted always in the organic farming, not following a defined trend the remaining systems. Over the 15-year period, the energy output/input ratio was <1 in all rotations for the conventional and conservation system in the extremely dry seasons. For barley monoculture, the ratio was <1 in seven seasons under conventional management, in eight seasons under conservation management, and in five under the organic farming system. The highest energy ratios were achieved in the B–V rotation in the organic system, being above 5.00 in 10 of the 15 seasons involved in this study (data not shown).

The total yield obtained per unit of energy input (energy productivity) was significantly higher in organic farming (400 kg GJ^{-1}) than in either the conventional or conservation systems (173 and 177 kg GJ^{-1}, respectively) (Table 6). The value of this variable ranged from 360 kg GJ^{-1} for B–V to 137 kg GJ^{-1} for B–B (Table 7), and was highest ($P < 0.05$) in B–V for organic farming (572 kg GJ^{-1}; a result of the high values for both the barley and vetch crops) and lowest in B–B for both the conventional and conservation systems (101 and 95.4 kg GJ^{-1}, respectively) (Table 8). Considering individual crops in each rotation, vetch was the most energetically efficient crop (yield/input), especially in the organic system (654 kg GJ^{-1}), a result of the low requirements for producing a unit of vetch hay. Sunflower was only more efficient than barley in B–V and B–F under conservation system and than continuous barley, irrespective of the management system. Considering the individual seasons, the greatest energy productivity was always reached in the organic system (data not shown). Over the 15-year study, the highest yields per unit of energy input were achieved in 1995/96 for the organic system (673 kg GJ^{-1}) and in 1999/00 for the conservation and conventional systems (326 and 270 kg GJ^{-1}, respectively). The lowest were seen in the dry year of 1994/95 (16.8 kg GJ^{-1}, 26.5 kg GJ^{-1}, and 115.4 kg GJ^{-1} for conventional, conservation and organic farming, respectively) (data not shown).

4. Discussion

The present study compared the energy balance associated with three farming systems and four barley-based crop rotations under semi-arid Mediterranean climate conditions of central Spain over 15 years. All experiments took place at the same site and the same cultivation practices and crop rotations, widely employed by local farmers in the area of the study, were used throughout. The rainfall amount and distribution varied greatly each year, affecting crop yields, and consequently, energy outputs and the energy balance. Thus, the amount and opportunity of precipitations, fundamental aspect in semi-arid Mediterranean climates, affected not only the development of the different phenological crop stages (and, as results, crop yields), but also the chemical fertilization efficiency and the nutrient cycled. The present results therefore provide a solid reference for these crops grown in this way under semi-arid environments.

Energy analysis investigations have been undertaken worldwide to compare different farming systems and crop rotations, among others variables. Dalgaard et al. (2001), Jørgensen et al. (2005), Gündoğmuş (2006), Gündoğmuş and Bayramoğlu (2006), Hoeppner et al. (2006), Bos et al. (2007), Caporali et al. (2007), Klimeková and Lehocká (2007), and Baum et al. (2009), among others, compared organic and conventional systems; Hernanz et al. (1995), Borin et al. (1997), Zentner et al. (1998, 2004), and Rathke et al. (2007) compared conservation systems (minimum tillage, zero tillage) and conventional systems; Pervanchon et al. (2002), Pacini et al. (2003) and Helander and Delin (2004) compared conventional, ecological and integrated management systems; Gelfand et al. (2010) compared organic, conservation and conventional cropping rotations under high and evenly distributed rain conditions; Hernanz et al. (1995), Zentner et al. (1989, 1998, 2004), Risoud (2000), Hülsbergen et al. (2001) and Rathke et al. (2007), compared different crop rotations, most of them including monoculture and crops grown on fallow land. However, differences in the methodology, farm location, pedo-climatic conditions, etc., impede – and in some cases rule out – the comparison of these studies. Another aspect to be considered is the great difference in the energy coefficients reported in the literature, which can affect the conclusions derived from these studies when differences among treatments are small.

In previous studies, energy inputs averaged 7.10 GJ ha^{-1} for continuous wheat and 3.48 GJ ha^{-1} for a fallow-wheat rotation under conventional tillage (Zentner et al., 1984). This behaviour was later confirmed by Zentner et al. (1998), although with lower values. These authors also found, and later confirmed in a 12-year experiment (Zentner et al., 2004), that the total energy use of complete cropping systems differed significantly with the crop rotation employed, but was unaffected by the tillage method (conventional, minimum or no-tillage): the fuel (non-renewable energy input) savings obtained in the conservation system were compensated for by greater herbicide and N fertilizer requirements. However, in relation to this last aspect, Cantero-Martínez et al. (2003) argued that no additional fertilizer is needed when minimum tillage or no tillage is used in Mediterranean semi-arid, rainfed conditions. When comparing different crop rotations in semi-arid central Spain, Hernanz et al. (1995) found that energy consumption under conventional tillage was about 10% greater than that associated with conservation with minimum or no-tillage in all the rotations they contemplated; this agrees with the present results. However, these authors indicated their fallow-cereal rotation to show the greatest energy demand owing to the larger amounts of fuel used in conventional and minimum tillage, and to the higher consumption of herbicide in no-tillage. In agreement with Rathke et al. (2007), the present results confirm the importance of fertilizer in the total energy input in conventional and conservation systems, followed by fuel. The difference between the conventional and conservation managements was due to the greater use of machinery (and consequently of fuel) in the former, although the use of herbicides was slightly lower, in agreement with Zentner et al. (1998, 2004).

In the present work, the conservation and (especially) the conventional farming systems were largely dependent on energy sources (both direct and indirect) in comparison with organic farming. This dependence was greater in barley monoculture and lower in the B–F rotation for all three types of management. These differences between crop rotations were less marked in organic farming than in the other two systems. In all cases, barley was the most energy-consuming crop, in agreement with Hernanz et al. (1995), a consequence of its high fertilizer and seed requirements. The least energy-consuming crop was sunflower, mainly because of the low seed input.

Average energy outputs were lowest in the organic system, in concordance with Risoud (2000), Jørgensen et al. (2005) and Klimeková and Lehocká (2007), a result of lower crop yields (with the exception of sunflower). However, soil degradation, measured as a decrease in the soil organic carbon throughout the experiment, was not observed in this management treatment (data not shown), although no additional organic matter was supplied. The reason why the fields tend to a balance when they are cultivated without external nutrients and maintain the yields indefinitely in a lower level, is that soils receive a continued flow of natural form nutrients proceeding from diverse sources (Loomis and Connor, 2002). Thus, the results obtained show the importance of the small flows of nutrients (in this case proceeding from the crop residues, the legume symbiotic nitrogen and the own soil) in poor agro-systems.

It is important to consider that the use of sustainable practices needed to obtain the yields in organic farming resulted in reduced yields, but the increase of yields with the use of agrochemicals for other systems is at expense of an increase in the energetic costs, and consequently, in the CO_2 emissions and environmental impact.

The results of energy outputs for the conventional and conservation systems were in general agreement with those of Zentner et al. (1998) for continuous wheat (20.7 and 21.2 GJ ha^{-1} in conventional and no-tillage systems, respectively) and for a wheat-fallow rotation (21.0 and 16.2 GJ ha^{-1} in conventional and no-tillage systems, respectively).

Considering the whole period of the study, a certain relationship between energy requirements and crop yields (and therefore with energy output) was observed. Thus, the conventional system was the most energy consuming but the most productive system, about 10% higher than conservation system. In dry seasons, however, this relationship was not observed: the highest energy outputs were obtained in the organic (low input) system (data not shown), which suggests the low efficiency of chemical fertilizers in these conditions.

Borin et al. (1997) indicated that energy output was higher under a conventional than a no-tillage system. Zentner et al. (1998, 2004) and Rathke et al. (2007), however, found that the tillage method had little influence on the energy output in different cropping sequences.

In the present work, the inclusion of a leguminous forage crop (vetch) increased the total energy output under all systems, in agreement with Hernanz et al. (1995) and Rathke et al. (2007). The B–F and B–B rotations were energetically the least productive rotations. It should be remembered, however, that the grain yield for B–B, under both the conventional and conservation systems, was similar to that obtained in the B–F rotation, although in the latter case yields corresponded to half of the plot (the other half was left in fallow, with no crop), equivalent to the whole plot every two years. Thus, the barley grain productivity is double when alternating with fallow than in monoculture. For individual crops, barley showed the greatest energy output and sunflower the smallest. Risoud (2000), however, reported that energy output increased in the order wheat $<$ lentil $<$ sunflower in an organic fallow-sunflower-lentil-wheat rotation.

The energy efficiency of a productive system can be measured as net energy, energy output/input or energy productivity. Net energy increases as long as the energy output per unit energy input increases (Rathke et al., 2007). It should be maximum when the availability of arable land is the limiting factor for plant production (Hülsbergen et al., 2001) or when the land is used to produce renewable energy (Kuemmel et al., 1998). The review by Zentner et al. (1989) indicates that the ‘net energy produced’ is a more desirable measure of energy efficiency than the output/input ratio since the absolute quantities of energy to calculate net energy are stated. Energy productivity is a measure of the environmental effects associated with the production of crops. This variable can therefore be used to determine the optimum intensity of land and crop management from an ecological point of view (Hülsbergen et al., 2001). Fluck and Baird (1982) and Hernanz et al. (1995) consider that this energy parameter is more appropriate for the comparison of alternating crop production systems since it does not depend on the calorific content of the product. Energy productivity and energy output/input are measures of the environmental effects associated with the yields of crops (Rathke et al., 2007).

Zentner et al. (2004) found that net energy output showed a behaviour generally similar to that of energy output. The present results are only partially in agreement with this, since the organic system produced the lowest energy outputs. However, it was also associated with highest net energy output since the reduction in inputs was greater than the reduction in outputs, even in the years with adverse weather. With respect to the crop rotations, the B–V rotation had the highest energy output and net energy since the increase in energy output was greater than the increase in energy inputs. The B–B rotation was associated with the lowest net energy, a result of the high energy input required.

Borin et al. (1997) and Rathke et al. (2007) observed that the output/input ratio tended to increase when soil tillage operations were reduced. In the present work, however, this trend was not observed. As mentioned above, energy inputs for the conservation system were 10% lower than for the conventional system, with a reduction in energy output of the same proportion. In the organic system, however, the energy ratio was 2.3 times higher than those seen in the other two systems since the reduction in energy inputs was more marked than the reduction in energy outputs. Thus, for the whole period, the organic system produced 5.36 units of energy output for every one unit of energy input spent, while the conservation and conventional systems returned 2.35 units.

In agreement with Hernanz et al. (1995) and Rathke et al. (2007), the crop rotation involving a leguminous plant (vetch) provided the highest energy output/input ratio, especially under organic management. The least energetically efficient rotation was B–B, especially under the conventional and conservation systems, as reported by other authors (Hernanz et al., 1995; Zentner et al., 1998), with values of 2.00. Zentner et al. (1998, 2004) noticed that conservation management generally enhanced the energy output/input ratio for mixed rotations under semi-arid conditions, but not for monoculture cereal rotations. In the present case, however, this trend was not so clear.

Jørgensen et al. (2005) observed that the energy productivity of a barley crop was only marginally lower under organic management than under conventional management, since the yield and energy requirements in the former system were reduced in the same proportion as in the latter. In the present study, however, energy productivity followed a similar trend as for the energy output/input ratio, in agreement with Zentner et al. (1998), and vetch for forage was the most efficient crop. The energy requirements per kilogram of barley grain were practically double in the B–B than in the B–F rotation since, as mentioned above, the energy inputs were approximately half in B–F than in B–B and the yields obtained, however, were practically the same. Sunflower was the least energy-efficient crop in all cases since yields (and consequently energy outputs) were low (crops grow in summer with low rainfall). However, the inclusion of sunflower in the barley rotation could be justified since it improves soil structure and helps provide weed control (Lacasta et al., 2007).

In relation to these last energy parameters (output/input ratio, energy productivity), it is important to take into account that the interpretation of the results could lead to misleading conclusions when inputs are reduced (small denominator) but at expense of soil erosion, soil organic matter decrease and overall sustainability, aspects not shown in the organic (low input) management, as previously exposed.

5. Conclusions

The results of energy balance obtained in this 15-year study, considering as inputs the factors supplied and controlled by farmers, indicate that farming systems requiring agrochemicals in semi-arid Mediterranean conditions, whether conventional or conservation (no tillage), appear to be little efficient regarding energy. Chemical fertilizer was the most important energy input in the conventional and conservation systems studied, but their use did not lead to an equivalent increase in yield because of the irregular distribution and the lack of opportunity of the scarce rainfalls in many years, situation which will foreseeably get worse as consequence of the climate changes. The results suggest that fertilizer inputs were excessive for conventional and conservation systems, and due to its low efficiency in arid and semi-arid environments, chemical fertilization should be reduced. Organic (low-input) farming would appear to be suited better to the environmental conditions of Mediterranean drylands, more than doubling the energy efficiency (output/input) of the above agrochemical systems and offering a sustainable production over time with a minimal energy input. Cereal monoculture, independent of the crop management system used, appears to be an energetically unsustainable practice, especially in the driest seasons. However, crop rotations, especially those that include a leguminous crop, increase energy efficiency.

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