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Cover Crop as Living Mulch: Effects on Energy Flows in Mediterranean Organic Cropping Systems

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Received: 22 March 2020; Accepted: 7 May 2020; Published: 9 May 2020



Abstract: Sustainability of agricultural practices is one of the most important issues in organic agriculture and its assessment is crucial. To this aim, evaluating the balance between the energy inputs and outputs in crop rotations could be a valuable tool. Therefore, we compared different management strategies in a four-year organic cropping system, by estimating the energy balance of crop production. Two different living mulches with no-till (B1) and green manure (B2) were compared with a cropping system without cover crop (B3), performing both energy analysis and energy balance. Energy parameters were also evaluated. The energy input of fertilizers and water was more than 55% of the total energy required by the cropping systems, suggesting that these agronomic practices should be tailored by farmers to decrease total energy inputs. The potential energy output was significantly higher in the B1 than the B2 and B3 cropping systems (20% and 54%, respectively). Results indicated that B1 and B2 could enhance the energy outputs without negatively affecting the energy consumption, since these cropping systems also showed higher energy efficiency. The introduction of the cover crop as living mulch combined with no-till could be a powerful tool to enhance systems sustainability, without compromising the crop yields.

Keywords: agro-ecological services crops; energy analysis; energy use efficiency; green manure; no-till roller crimper; organic agriculture

1. Introduction

The European commission [1] has defined the organic agriculture as a production system, based on an agro-ecosystem management approach, which sustains the health of soils, ecosystems, ecological production methods, biodiversity and cropping systems adapted to local conditions. A low external-input-based cropping system can reach a good compromise between crop production intensity and efficiency in the agricultural agro-ecosystems [2,3]. The organic agriculture approach promotes lowest soil disturbance, permanent/semi-permanent soil cover and the joint use of crop rotations, organic fertilizers and soil amendments to increase or preserve soil organic matter content.

Among agro-ecological management practices, agro-ecological service crops (ASC) can play a key role for the sustainability of the cropping systems [4], since they may be used as ecological compensation areas or as “break crops”. The ASC could be utilized in the rotation between two consecutive cash crops, or intercropped with a cash crop and maintained as a living cover during the growing cycle as living mulch (LM). The potential of ASC as LM to provide ecological services could be showed as an increase of biodiversity, containing or suppressing weeds [5], adding soil organic matter to soil and improving soil physicochemical characteristics [6], reducing losses of nutrients, containing water run-off effects [7] and providing nitrogen (N) if legume cover crops are used [8,9]. On the other hand, the LM could reduce cash crop yield both on arable [10] and vegetable crops [11], due both to the ASC and cash crop

competition for resources and/or nutrients, and to their temporary immobilization. Indeed, there are contradictions in the published studies evaluating the crop responses to ASC introduction as LM, and the effects on both cash crop yields and soil properties [3]. The success of LM systems depends on ASC species and their establishment in relation with the cash crop planting date [12,13], ASC weed management strategies [14], N dynamics [15] and seasonal climatic conditions [4].

There is a need to find out which ASC could be used as mulch and the different termination strategies to improve both agronomic performance and systems environmental sustainability. The methodologies analyzing the environmental performances either for a product or in a production system, may be very helpful to evaluate the sustainability in the agricultural systems. Different authors [16,17] have suggested energy analysis (EA) as one of these methodologies. According with the definition of Alluvione et al. [18], energetic sustainability in agriculture implies the efficient use of nonrenewable resources (i.e., machinery, fuels and chemicals) and the progressive substitution of nonrenewable with renewable ones (i.e., human labor, seeds, water and organic fertilizers). On this matter, the implementation of the above described agronomic practices could contribute to promote renewable energy savings. Therefore, both the analysis and the knowledge of the balances between the energy inputs and outputs in the cropping systems is one of the most important steps to reach systems sustainability, especially in organic agriculture. The EA determines the energy hotspots of the production system, and it may help to save considerable amounts of energy, at the same time increasing the mitigation of environmental impacts [19]. In fact, the EA aids identifying the reasons for energy over-consumption, so defining which elements of the cropping system should be further improved, as also found by Diacono et al. [13]. The ASC no-till management, in crop rotation across a wide range of European pedoclimatic conditions, has proved to improve the environmental performance of cropping systems [14], by increasing the potential energy that can be recycled within the systems. Therefore, the EA allows us to investigate how to improve the whole systems efficiency [20].

There is still a lack of knowledge on the sustainability assessment of introduction of cover crops in organic systems over a mid/long-term period under Mediterranean conditions. Therefore, the objective of this research was to compare the effects of two leguminous crops with different management strategies in a four-year organic crop rotation (eight cropping cycles) and to evaluate them in terms of the energy balance of crop production. To accomplish this aim a perennial ASC was compared to an annual one (alfalfa and clover, respectively). These different systems were compared, following the study of Moreno et al. [21], under the same pedoclimatic conditions by using the same methodology, in order to better estimate the EA.

2. Materials and Methods

2.1. Study Site and Field Experiment

The study was conducted in the “MITIORG” organic long-term field experiment of the Council for Agricultural Research and Economics—Research Centre for Agriculture and Environment located at Metaponto (MT) in southern Italy (lat. 40°24′ N; long. 16°48′ E). The climate of the study area is characterized by an accentuated thermo-Mediterranean climate [22], with the mean long-term average (30 years) temperature of about 17.1 °C. The average rainfall is about 500 mm year⁻¹, concentrated mainly in the winter season and with drought periods in the summer (Figure 1). The soil is classified as Typic Epiaquert [23]. It has a clay loam texture (19, 39 and 42% of sand, loam and clay, respectively), with pH of 7.8, 0.48 mS electric conductivity, and about 25 g kg⁻¹ of organic matter.

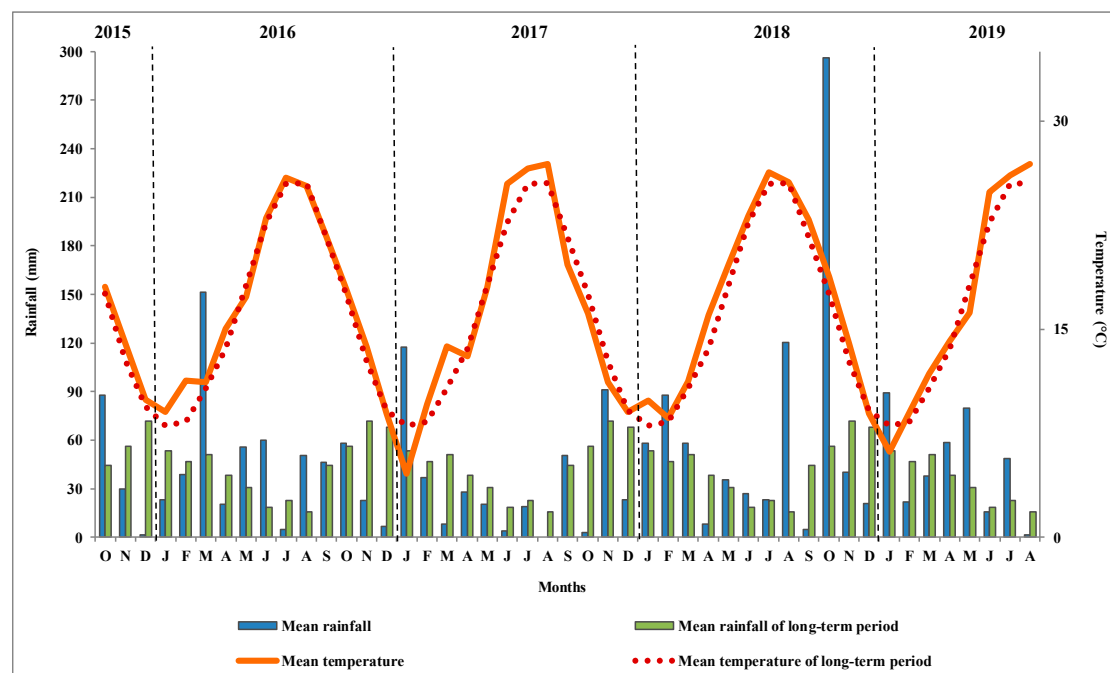


Figure 1. Mean monthly temperatures and rainfall during experiment (2015–2019) in comparison with the long-term (1981–2018) averages.

Mean monthly rainfall and temperatures data were recorded for each season in the nearby weather station, and in Figure 1 they are compared with the long-term averages (from 1981 to 2018). The mean annual temperatures were quite similar to the long-term average (13.5 °C). However, there was an extreme event in January 2017, unusual for the experimental area, with very low mean temperatures (4.5 °C) and peaks below -4 °C, associated with a high rainfall intensity (117 mm). The total amounts of rainfall were 538, 401, and 781 mm in 2016, 2017 and 2018, respectively, being different by +4%, −23% and +51% than long-term value (518 mm), with a flood event in October 2018.

The aim of the MITIORG experiment is to test a set of different agro-ecological practices combined and integrated to adapt organic vegetable production to climate change conditions and extreme events (such as drought alternating with flooding). These agro-ecological techniques are: soil surface shaping with raised bed (ridges 2.5 m) and flat areas (or strips) of the same width; cash crops rotation; ASC introduction both as break crops or LM; ASC termination techniques, such as green manure (GM) and flattening with a no-till roller crimper technique (NT); and different organic fertilization strategies. Additional information about the long-term experiment is reported in Diacono et al. [24].

2.2. Experimental Setup and Treatments

The research was carried out on four different organic horticultural crops in rotation: (i) cauliflower—*Brassica oleracea* L. var. Botrytis, cv. Triumphans; (ii) tomato—*Solanum lycopersicum* L., cv. Donald; (iii) fennel—*Foeniculum vulgare* Mill., cv. Aurelio; (iv) zucchini—*Cucurbita pepo* L., cv. President). These crops were cultivated on the ridges in two cropping seasons for each crop for four years (from 2015 to 2019). The cover and the cash crops time sequences are reported in Figure 2.

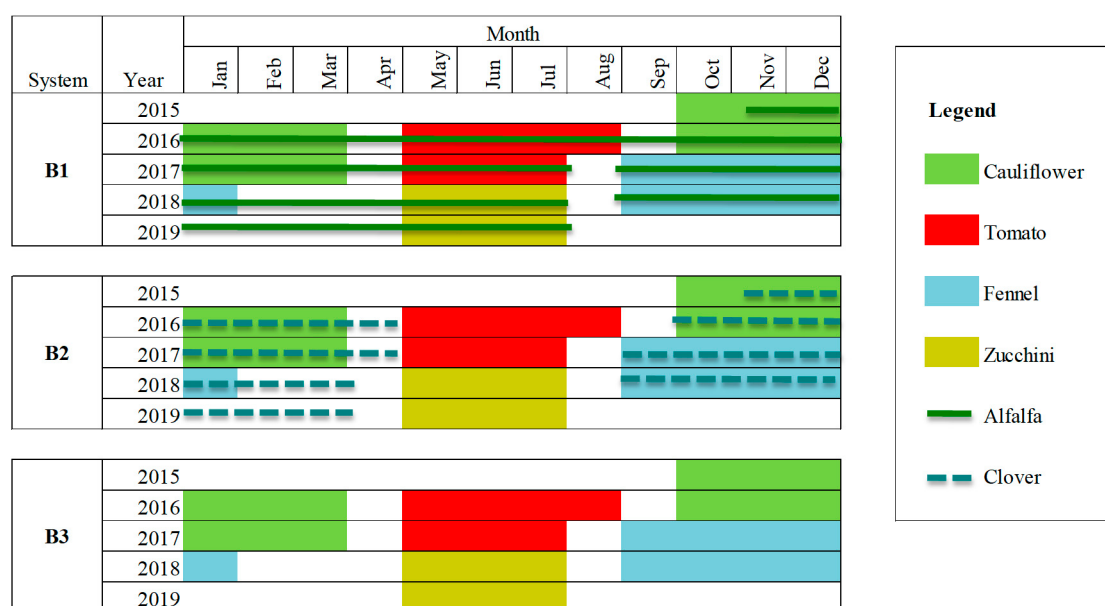


Figure 2. Time sequence of the cash crops and the agroecological service crops (ASC) throughout the four-year experiment divided by three different cropping systems. (B1 = alfalfa as living mulch during both winter and summer periods, flattened with a no-till roller crimper; B2 = clover as living mulch during the winter period, chopped and plowed as green manure; B3 = control without ASC).

The following three different management strategies were compared: (B1) alfalfa (*Medicago sativa* L., cv. Garisenda) as LM during both winter and summer periods, flattened with a no-till roller crimper (NT) at the end of the cash crops and mowed during cash crop cultivation; (B2) clover (*Trifolium incarnatum* L., cv. Tiogene) as LM during the winter period, chopped and plowed as GM into the soil before summer cash crop transplanting and mowed during the winter cash crop; (B3) control without ASC.

In each year, a commercial organic fertilizer was applied one week before the ASC termination and cash crop transplanting at the total N rate as reported in Table 1, in accordance with production rules in organic agriculture and based on the N uptake. The management of pathogens and the phytosanitary control were the same in each plot, according to the European regulation for the organic productions. The transplanting distances were slightly different and, in particular, they were lower in the B1 treatment to optimize ASC management.

The experimental design was a strip plot with three replications. The elementary plot was 24 m long and 2.5 m wide (i.e., 60 m²). The description of the inputs used in the systems is reported in Table 1.

2.3. Energy Analysis and Measurements to Evaluate the Environmental Sustainability of the Systems

To assess the sustainability of the three different management practices adopted in the experiment, the energy balances were determined according to the procedures described by Persiani et al. [17]. The input and output factors were quantified for each item directly in the experimental farm. In particular, the energetic flows were calculated by means of different factors that can be identified in the following inputs: human labor, machinery and fuels, fertilizers, chemicals, seeds and plants, plastics, water and pesticides. The same procedure was adopted for the outputs by identifying: crop yields, ASC, weeds and cash crop biomasses (residues after crop harvest). We have recorded the data (inputs and outputs) from experimental field trials, which are sometimes slightly different from the farmers' fields. However, we tried to simulate, as much as possible, the operations of organic farmers.

Table 1. Total inputs of the three cropping systems carried out in the four-year experiment.

	B1	B2	B3
Phytosanitary management	Organic (copper, sulfur, pyrethrum, bacillus thuringiensis)	Organic (copper, sulfur, pyrethrum, bacillus thuringiensis)	Organic (copper, sulfur, pyrethrum, bacillus thuringiensis)
Irrigation system	Drip irrigation	Drip irrigation	Drip irrigation
Water consumption	24630 m ³ ha ⁻¹	24630 m ³ ha ⁻¹	24630 m ³ ha ⁻¹
Fertilization	Commercial organic fertilizer	Commercial organic fertilizer	Commercial organic fertilizer
N distributed	980 kg ha ⁻¹	980 kg ha ⁻¹	1080 kg ha ⁻¹
Human labor	3516 h ha ⁻¹	3291 h ha ⁻¹	3258 h ha ⁻¹
Fuels	875 L ha ⁻¹	850 L ha ⁻¹	778 L ha ⁻¹
Plastic materials	430 kg ha ⁻¹	430 kg ha ⁻¹	430 kg ha ⁻¹
Total number of Plants	238200 n. ha ⁻¹	226232 n. ha ⁻¹	226232 n. ha ⁻¹
Amount of ASC Seeds	200 kg ha ⁻¹	150 kg ha ⁻¹	-
Machinery mass (Mm) ^a	108 kg ha ⁻¹	121 kg ha ⁻¹	115 kg ha ⁻¹

^a $Mm = \sum (M \cdot t / L)$; Mm = Machinery and implement mass, M = mass (kg), t = duration of each operation (h ha⁻¹), L = lifespan of the machinery/implement (h).

Marketable yields (Mg ha⁻¹) and plants residues dry matter (Mg ha⁻¹) were determined from three randomly selected plants in each plot during the cash crops harvest. Furthermore, at ASC or crop cycle termination, aboveground biomass of ASC and weeds (in all treatments) was measured by clipping all plant materials at ground level within a half-meter-square area. Crop production, plant residues, ASC and weeds were dried at 70 °C for 48 h to obtain the dry weight of aboveground biomass (Mg ha⁻¹).

Their conversion to energy values, expressed for production unit (hectare), was obtained by using the corresponding energy coefficients (Table 2).

Moreover, the energy inputs (EI) were divided by main categories (e.g., human labor, machinery and fuels, fertilizers and chemicals, water and irrigation equipment, seeds and plants), main operations (soil preparation and ASC weeds control, cash crop management, fertilization) and crop species (cauliflower, tomato, fennel and zucchini) [17,25]. They were also divided into renewable and nonrenewable, as well as direct and indirect input forms [26].

The energy output for each crop was reported both as marketable yield (Mg ha⁻¹) and as yield energy (YE), which was calculated as the calorific value of the product (MJ kg⁻¹) [27], multiplied by the corresponding crop yield (kg). The potential recyclable energy (PRE) was also determined. The PRE represents the energy in the ASC, weeds and cash crops biomass residues, multiplied by their corresponding coefficient of equivalent energy (Table 2).

The total energy output (EO) calculated as the sum of YE + PRE was divided by each crop. Finally, the energy-recycling ratio (ERR), energy-use efficiency (EUE) and net energy (NE) were estimated as: $ERR = PRE/YE$ ([14]), $EUE = EO/EI$ ([25]), $NE = EO - EI$ ([25]).

2.4. Statistical Analysis

The standard deviation analysis was carried out by using Microsoft Office 365 to verify the effect of the treatments on the outputs. According with the procedure reported by different authors [17,18,25] we did not calculate standard deviations for the inputs since, among the different repetitions in the same thesis, the inputs used were not modified (i.e., we had the same amount of fertilizers, machinery usage times for tillage operations, water consumption, etc.). As a consequence, it is not possible to carry out a variability analysis. As a matter of fact, in this kind of sustainability analysis, the variability analyses are likely not necessary.

Table 2. Energy equivalents (MJ unit^{−1}) of farm facilities for crops production.

Inputs	Unit	Energy Equivalent (MJ unit ^{−1})	References
Human labor	h	1.96	[14]
Machinery	kg	62.7	[14]
Fuels			
Diesel	L	56.31	[14]
Fertilizers			
Nitrogen (N)	kg	60.6	[17]
Phosphate (P ₂ O ₅)	kg	11.1	[17]
Potash (K ₂ O)	kg	6.7	[17]
Chemicals			
Insecticides	kg	199	[17]
Copper	kg	78.2	[14]
Sulfur	kg	7.1	[14]
Irrigation water	m ³	1.02	[17]
Plastic pipes PE	kg	120	[17]
Seeds	kg	14.7	[14]
Plantlets	n	0.2	[14]
Outputs			
Cauliflower	kg	1.04	[27]
Fennel	kg	1.29	[27]
Tomato	kg	0.75	[27]
Zucchini	kg	0.7	[27]
Biomass residues	kg	0.3	[14]

3. Results

3.1. Outputs, Energy Consumptions and Energy Outputs of the Cropping Systems

The treatments effect on cauliflower, tomato, fennel and zucchini marketable yields in each cropping season are reported in Table 3.

Table 3. Effects of the three different management strategies on cauliflower, tomato, fennel and zucchini marketable yield (Mg ha^{−1}) (B1 = alfalfa as living mulch during both winter and summer periods, flattened with a no-till roller crimper; B2 = clover as living mulch during the winter period, chopped and plowed as green manure; B3 = control without ASC).

Year	Crop	B1			B2			B3		
		(Mg ha ^{−1})			(Mg ha ^{−1})			(Mg ha ^{−1})		
2015–2016	cauliflower	9.46	±	2.38	9.86	±	1.25	5.77	±	1.06
2016	tomato	5.33	±	2.19	20.73	±	6.33	15.65	±	8.14
2016–2017	cauliflower	0.46	±	0.20	0.47	±	0.67	0.00	±	0.00
2017	tomato	27.07	±	2.11	13.55	±	3.33	12.86	±	1.29
2017–2018	fennel	19.02	±	1.61	23.31	±	0.31	22.78	±	3.07
2018	zucchini	42.36	±	18.27	31.33	±	5.33	29.80	±	3.51
2018–2019	fennel	13.35	±	1.59	14.34	±	1.81	12.54	±	1.50
2019	zucchini	12.71	±	5.48	26.31	±	1.98	18.80	±	4.06

In 2015–2016 season, the highest value of cauliflower marketable yield was found in the B2 and B1 systems, whereas the B3 treatment showed a reduction of 42% and 39% compared with B2 and B1, respectively. Tomato had a higher production in the B2 system (20.73 Mg ha^{−1}) followed by B3 (−24%) and B1 (−74%) systems.

In the second season, the average cauliflower marketable yield drastically decreased compared to the 2016–2017 season, being less than 0.5 Mg ha^{-1} in all the systems. In the tomato crop, differently from what observed during the first year, the highest marketable yield value was found in the B1 system, being higher by 100% and 111% than B2 and B3, respectively.

Comparable values were found among the different management strategies both in the 2017–2018 and 2018–2019 seasons of fennel cultivation. However, the average fennel marketable yield in the 2018–2019 decreased by 38% in comparison with 2017–2018. In 2018, B1 determined the highest value in zucchini marketable yield, even if the treatments had no significant difference due to the high standard deviation value for B1 treatment. In the second year of zucchini cultivation (2019), again there was a decrease in the average values compared to the 2018 season, and the B1 and B3 treatments showed the lowest absolute values, with a reduction of 52% and 29%, respectively, compared to the B2 system.

The values of energy consumed (GJ ha^{-1}) during the four-year rotation were divided by the input categories, crop operations and cash crop (Table 4). The B1 systems consumed the maximum amount of energy (272.4 GJ ha^{-1}) followed by B3 and B2 (269.1 and 266.5 GJ ha^{-1} , respectively), even if the differences were negligible. Among the categories, the energy used in the systems by fertilizers and chemicals had the highest contribution to total energy input in all treatments (34.0%, 34.8% and 37.8%, in B1, B2 and B3, respectively), followed by water and irrigation equipment (28.2%, 28.8% and 28.5% in B1, B2 and B3, respectively). On the contrary, human labor required the lowest amounts of energy. Among crop operations, the highest amounts of energy were required for the cash crop management in all cropping systems, reaching about 50% of the total energy. Conversely, the lowest energy consumption was recorded by soil preparations and ASC/weeds control, which showed values lower than 15% in all cropping systems. The energy analysis by cash crop showed that tomato required the greatest amount of energy in all treatments, reaching values of 74.4 , 72.6 and 81.5 GJ ha^{-1} in the B1, B2 and B3, respectively. In particular, in the B3 cropping system, the tomato crop required more than 30% of the total energy. In the other systems the energy consumption of the cash crop was quite similar between them.

The indirect energy was the greatest part of the total energy inputs (Table 4d), without any substantial difference among the systems (around 71%). Moreover, the renewable energy reached 59.1%, 58.4% and 60.5% of the total energy inputs in the B1, B2 and B3 systems, respectively (Table 4e).

The B1 system produced 10.99 GJ ha^{-1} of energy in the ASC/weeds and cash crop biomass residues (PRE), being significantly higher than B2 and B3 systems (Figure 3a), with an increase of 20% and 54% respectively. The sum of the energies over the years and crop sequences (Figure 3b), showed that the mean YE was significantly lower for the control (B3) ($116.68 \text{ GJ ha}^{-1}$) than the system with clover (B2) ($136.88 \text{ GJ ha}^{-1}$). The B1 system had an intermediate energy production ($125.92 \text{ GJ ha}^{-1}$), statistically comparable to the other treatments. Figure 3c shows that the zucchini was the most productive crop, which reached a total energy output (EO) value of 51.4 GJ ha^{-1} as average among all treatments, representing the 38.1% of the EO. The other crops reached 35.3%, 18.8% and 7.8% for fennel, tomato and cauliflower, respectively. A comparison of the different systems indicated that B2 and B1 had a similar and not statistically different EO, while B3 was 15.5% and 11.1% lower than B2 and B1, respectively.

Table 4. Amounts of energy inputs, consumed in the four year rotations, expressed as total energy equivalents (GJ ha^{-1}) and percentage of total energy input (%) divided by categories (a), crop operations (b), cash crop (c), direct/indirect (d) and renewable/no renewable energy (e) (B1 = alfalfa as living mulch during both winter and summer periods, flattened with a no-till roller crimper; B2 = clover as living mulch during the winter period, chopped and plowed as green manure; B3 = control without ASC). The values are based on the whole four-year rotation.

		B1		B2		B3	
a: Categories		GJ ha^{-1}	%	GJ ha^{-1}	%	GJ ha^{-1}	%
	Human labor	6.89	2.53	6.45	2.42	6.38	2.37
	Machinery and fuels	57.95	21.27	57.53	21.59	53.07	19.72
	Fertilizers and chemicals	92.69	34.02	92.69	34.78	101.64	37.77
	Water and irrigation equipment	76.72	28.16	76.72	28.79	76.72	28.51
	Seeds and plants	38.18	14.01	33.09	12.42	31.33	11.64
b: crop operations							
	Soils preparations and ASC/weeds control	40.43	14.84	39.48	14.81	33.18	12.33
	Cash crop management	139.15	51.08	134.15	50.34	134.15	49.84
	Fertilization	92.85	34.08	92.85	34.84	101.80	37.83
c: Cash crops							
	Cauliflower	67.80	24.89	65.70	24.65	61.90	23.00
	Tomato	74.38	27.30	72.60	27.24	81.55	30.30
	Fennel	61.37	22.53	60.96	22.87	58.84	21.86
	Zucchini	68.88	25.28	67.23	25.23	66.85	24.84
d: Direct/indirect							
	Direct	81.30	29.84	79.39	29.79	75.34	27.99
	Indirect	191.13	70.16	187.10	70.21	193.80	72.01
e: Renewable/no renewable							
	Renewable	161.12	59.14	155.59	58.39	162.71	60.46
	No renewable	111.31	40.86	110.90	41.61	106.43	39.54
	Total inputs	272.43		266.49		269.14	

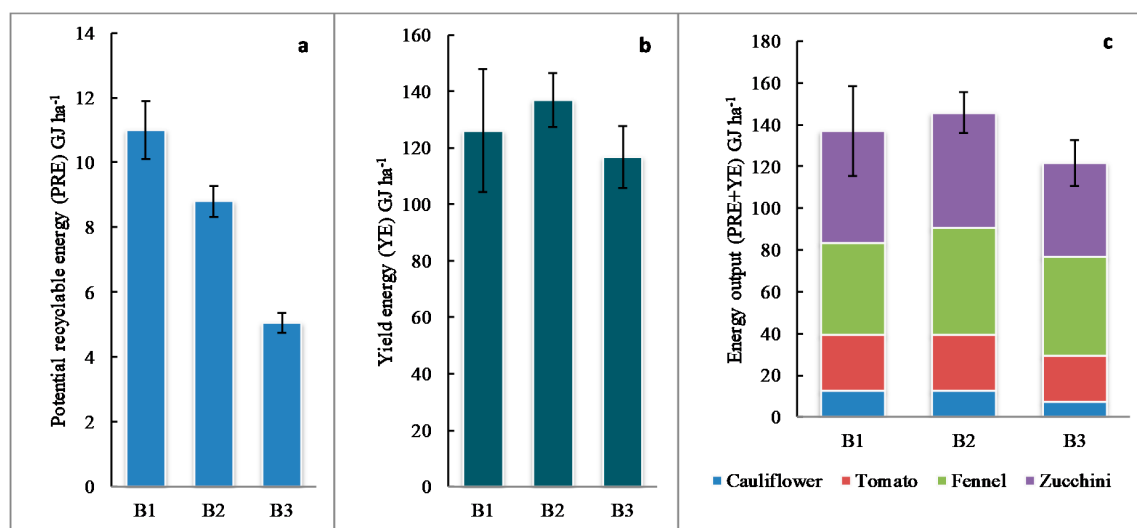


Figure 3. Energy output (GJ ha^{-1}): (a) potential recyclable energy (PRE) (ASC + weeds + plant biomasses); (b) yield energy (YE); (c) PRE + YE divided by crops (B1 = alfalfa as living mulch during both winter and summer periods, flattened with a no-till roller crimper; B2 = clover as living mulch during the winter period, chopped and plowed as green manure; B3 = control without ASC).

3.2. Energetic Indicators of the Cropping Systems

Figure 4 shows the ERR, energy efficiency and net energy divided by cropping systems. The overall average of ERR was 6.5—the mean of the three cropping systems. The B1 showed the highest value (8.7), while B3 was the system with the significantly lowest potential recyclable energy, with a value of 4.3 (Figure 4a).

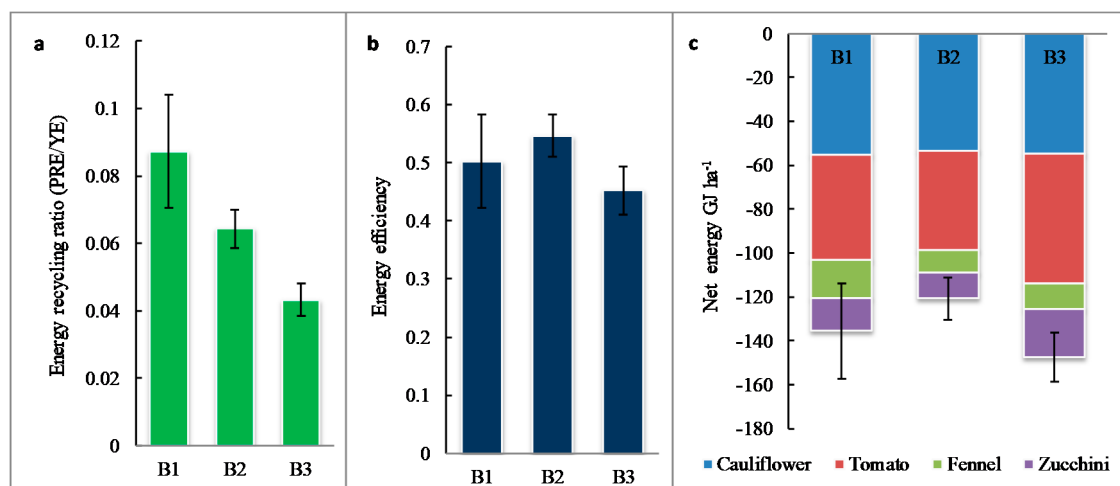


Figure 4. Energy parameters: (a) PRE/YE; (b) energy efficiency ((PRE + YE)/INPUT); (c) net energy (GJ ha⁻¹) (PRE + YE – INPUT) divided by crops (B1 = alfalfa as living mulch during both winter and summer periods, flattened with a no-till roller crimper; B2 = clover as living mulch during the winter period, chopped and plowed as green manure; B3 = control without ASC).

The overall average of EUE was 0.5 (mean of the three cropping systems). The B2 system was the system with the most energy use-efficient, reaching a value of 0.55. This value was significantly higher compared to the B3 system (showing a value of 0.45) (Figure 4b), considering both their mean values and standard deviations. The B1 system presented an intermediate value (0.5 output/input ratio), not significantly different compared to the other two systems. Figure 4c indicates that the overall average of NE (mean of the four-year period of the experiment) was $-134.57 \text{ GJ ha}^{-1}$. The total values of NE (histograms) were the sum of the crops (different colors) and the overall standard deviations among cropping systems were calculated. For total NE, the B1 and B2 systems reached similar results, whereas the total NE in B3 was -26.6 and -11.9 GJ ha^{-1} lower than B2 and B1, respectively, but significant differences were only found compared to B2. Among the different crops, reported in the Figure 4c as different colors, the fennel and zucchini produced similar and slightly negative results in all treatments (-13.0 and -16.3 GJ ha^{-1} for fennel and zucchini, respectively). Tomato and cauliflower crops showed higher NE values in all systems (-54.4 and -50.9 GJ ha^{-1} , respectively).

4. Discussion

4.1. Output, Energy Consumptions and Energy Outputs Analysis

The marketable yield results of the cauliflower crop showed higher production in the systems that included the leguminous ASC in the rotation rather than no ASC treatment, confirming the study of Diacono et al. 2018 [13]. However, during the second year, cauliflower production was particularly influenced by the low temperature during the winter, which determined a considerably lower value compared to the first year. In the tomato crop, during the first year the high biomass of alfalfa in the B1 system caused a yield reduction, likely due to the competition between the ASC and the cash crop. Conversely, the different weather conditions during the spring (being drier than the first year),

combined with the biomass incorporated into the soil during the previous season, determined an increase of production in B1.

The different treatments did not significantly affect fennel production, which was slightly higher in B2. The results of the second year of cultivation suggest that the flooding in October 2018 (Figure 1) likely determined higher marketable yield values in 2017–2018 than in 2018–2019. The B1 system showed a higher zucchini production during the 2018, although the values were comparable with the other treatments. Conversely, in the second year B1 showed the lowest value. The total rainfall during spring 2019 was higher by 54% and 43% than in the same period of 2018 and the long-term period, respectively, and this difference produced high alfalfa biomass in the 2019 season. The cash crop yield difference between the two years, similarly with what has been observed for tomato, could probably be due to the higher ASC competition, but it could also be due to nutrient immobilization by microbial degradation of carbon residues [13].

The total amount of the energy required during the four-year experimental trial was similar among the different management strategies. This would indicate that organic agronomic practices did not affect the inputs of the cropping systems. However, the analysis of energy requirements in the different crop rotation systems confirmed the primary importance of the fertilization strategies for the systems sustainability. This last result is in agreement with other studies in the Mediterranean area [17,21,28]. In our research, differently from the results reported in similar studies [18,29], but in agreement with some others [30,31], the energy consumed for the irrigation (considering both water and plastics for the irrigation equipment) represented the second most important input. Such energy requirement was higher than that by the fuels and machinery (28.5% and 20.9%, respectively). This behavior was likely due to different method of calculation, since many studies do not consider the irrigation equipment in the EA estimation. It could be also due to different experimental conditions (field trial conducted in rain-fed cultivation) and, therefore, this production factor may present considerable variation. Indeed, in some cultivations (as in our case) irrigation can be among the most significant energy consumption inputs, but it becomes negligible in different cultivation conditions. Since in our findings the sum of energy inputs of fertilizers and water was up to 55% of the total energy required by the systems, higher attention to these agronomic practices should be given by the farmers. Furthermore, it could be taken into account that our experiment concerned organic vegetable production, which requires higher levels of fertilizer and irrigation than both for energy or industrial crops.

The results indicated that the systems with the introduction of legume ASC in the crop rotations may reduce the needs of fertilizers and, consequently, the energy related to the fertilization practices [11]. This finding, in addition to the known several indirect agro-ecosystem benefits, further supports ASC introduction in organic cropping systems [9]. Anyway, we did not investigate the ASC effects on soil health (and properties), which is one of the most important indirect benefits of the cover crops introduction in the cropping systems. Since this is not an easily measurable benefit, it could be estimated only with a specific experiment with both appropriate treatments and deep investigations. This was not the objective of our study. However, these new agro-ecological systems require more energy related to the ASC seeds, machinery and fuels for the sowing and ASC managements, in agreement with the findings of Navarro-Mirò et al. [14]. Furthermore, in the cropping system with alfalfa (B1), additional energy was required to control ASC regrowth to avoid competition with the cash crop. These findings confirmed recent results of research [11,32], which pointed out the importance of identifying the suitable ASC species, management strategies and relationship with the cash crop and cultivation environment, in order to optimize the crop rotations and to achieve the best sustainability performances.

In our experiment, the waste of energy due to the control of the re-growth of alfalfa in the B1 was balanced by the energy saving related to the no-till ASC termination, in comparison with the traditional GM utilized in the B2 system [14]. Another slight energy difference between the B1 and B2 systems was found for the human labor. This result is mainly associated with the harvest operations directly proportional both to the amount of yields and to the different number of transplanting plants (higher

in B1 cropping system). Once again, the energy associated to this index (human labor) is particularly important in organic vegetable production as compared to other crops, since many operations in horticulture are performed by hand.

The energy outputs showed significant differences among the cropping systems. In particular, the PRE was significantly higher in B1 than in B2 and B3, suggesting that the association of living mulch and no-till techniques increased the biomass to recycle. In any case, we would like to point out that the energy required (inputs), as well as the outputs described later, were recorded in the experimental field trial by scientists who tried to simulate farmer production, even if a slight difference between these two procedures could occur. However, we were looking for at the differences among organic agronomical practices, which are recorded in the same way and, therefore, the results obtained should be accepted worldwide. In particular, this result may be attributed to the highest biomass produced by the alfalfa cover crop and a higher presence of ASC during the four-year rotation. Several studies have reported the benefits to cropland derived from biomass recycling by incorporating it into the soil [3,4,33,34]. In particular, Lal [35] indicated that the higher production of biomass and the consequent recycling in farm soils could increase the soil organic carbon concentration, accumulation and sequestration rate. As a consequence, biomass recycling can support the meso- and microfauna in the agro-ecosystem [36]. Deng et al. [37] also pointed out that the production and recycling of biomass are two of the most important strategies for sequestering CO₂ from the atmosphere, thus allowing climate change effects to be mitigated.

The energy related to biomasses, which was the highest in the B1 cropping system, could support the positive ecological role of biomass recycling in closing the loop in organic agriculture and enhancing the adoption of the circular economy.

Several studies reported the yield benefits derived from the introduction of leguminous crops in the crop rotation systems [38–40]. In our study, the effects of minimum tillage system and the higher biomasses of alfalfa occurred in the B1 system induced a slight and not statistically significant yield reduction of the cash crops compared to the B2 system. Different authors [13,41] indicated that the reduction that we found in B1 system was due to the competition for water and nutrients between alfalfa and cash crops and the different mineralization rate generated by the ASC management and termination that, in clay-loamy soil, may generate N temporary immobilization and soil compaction phenomena.

4.2. Energy Indicators: Analysis of the Cropping Systems

The energy indicators showed that the crop rotations that include the ASC provided the highest energy-recycling ratio. Therefore, the introduction of the ASC enhanced the amount of energy that can be recycled in the crop rotations, in agreement with the results reported by Navarro-Mirò et al. [14]. The ratio between output and recycled biomass is strictly related to the ability of the system to improve soil fertility [18]. In our study, the conservation tillage system associated with LM (B1) showed the greatest value of this ratio, due to the highest biomasses produced by alfalfa, confirming soil fertility re-establishment potential.

The B1 and B2 crop rotations also provided the highest EUE, particularly if the GM management strategy was adopted, whereas the least energetically efficient rotation was the cropping system without cover crop. This result is in agreement with the findings reported by Hernanz et al. [42] and Diacono et al. [13]. The EUE is generally related to both higher crop yields and lower energy consumption [43]. In our study, due to the small differences in the total energy inputs recorded in the different systems, the EUE was directly proportional to the cash crop yields, which are high in organic vegetable production. Thus, the EUE indicator was the lowest in cropping system without cover crop (B3), mainly due to the lower yield values.

Rathke et al. [44] highlighted a NE increase when the energy output per unit energy consumed increases. In our study, which investigates organic vegetable crops and not energy or industrial ones, all cropping systems showed a negative NE value, mainly due to low values in the cauliflower and tomato productions. The highest NE values were observed by using the B2 strategy, even if no

significant differences were observed compared to the B1 system, but only with B3 systems. Such a result was due to the high output variability among the different crops/years. Similarly to YE and EUE, the system without cover crop (B3) showed the lowest NE value, while the B1 had an intermediate value and comparable to both B2 and B3. Therefore, the results of our four-year organic crop rotation indicated that the introduction of the cover crop as living mulch could be a powerful tool to enhance the sustainability of the systems, without compromising the crop yields. These findings are quite in agreement with the results reported by Canali et al. [4] and Adekiya et al. [33].

5. Conclusions

On the basis of the findings of this study, the hypothesis that the introduction of ASC as living mulch (both in B1 and B2 cropping systems) enhances the energy output, without negatively affecting the energy consumption, has been confirmed. The tested cropping systems also showed higher energy efficiency. In particular, the LM combined with no-till (B1) produced more biomass, thus recycled more energy, leading to higher sustainability than the systems with LM combined with green manure (B2) and crop rotation without cover crop (B3). Moreover, the analysis of the energy flows showed that the production factors are crucial in determining the efficiency of the agricultural systems. Among them, fertilization strategies and introduction of ASC, especially those including leguminous crops, play an important role to reduce the needs of fertilizers.

The need to improve the management of irrigation to achieve higher energy efficiency was also pointed out. The findings of this study indicated that the introduction of agro-ecological techniques could be a feasible solution to improve the sustainability in the organic crop rotations, since the cropping systems that included the ASC were more sustainable than the control without cover crops. However, further studies could be required to assess the efficiency of these agronomical practices in different soils, using different ASC species and investigating them in relationship with C and N dynamics.

Author Contributions: Conceptualization, F.M.; formal analysis, A.P.; writing—original draft preparation, A.P., F.M., M.D.; writing—review and editing, F.M., M.D. All authors have read and agreed to the published version of the manuscript.

Funding: This paper is a result of the research and projects conducted on the MITIORG field experiment (Long-term climatic change adaptation in organic farming: synergistic combination of hydraulic arrangement, crop rotations, agro-ecological service crops, and agronomic techniques), funded by the Organic Farming Office of the Italian Ministry of Agriculture.

Acknowledgments: The authors wish to acknowledge the work of Marco Favale and Angelo Raffaele Quaranta for the technical assistance and field management.

Conflicts of Interest: The authors declare no conflict of interest.

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