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Environmental and Energy Analysis of Two Orchard Systems: A Case Study in Mediterranean Environment

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Abstract: This paper aimed to analyse and compare the environmental and energy sustainability of two orchards (peach versus kiwifruit) located in Southern Italy using Life Cycle Thinking. To this end, anthropogenic energy, CO_2 emissions, biogenic energy and carbon gains were also considered through Life Cycle Assessment methodology and Energy Analysis. The C–CO_2 balance was calculated as the difference between total C–CO_2 stored in soil and trees, at the end of their life cycles, and orchards Carbon Footprint (CF). The results showed that the production of 1 kg of peaches caused minor impacts, especially with reference to CF (0.124 kg CO_2 eq against 0.145 for kiwifruit), while it required 1.56 MJ of energy against 1.32 MJ for kiwifruit. In both orchards the main sources of direct CO_2 emissions came from fuel combustion, nitrous oxide release by crop residue decomposition, and nitrogenous fertilizer distribution. Nevertheless, both orchards had sustainable environmental and energy results. Despite the management of the orchards releasing CO_2 and consuming energy, they showed a significant capacity to store CO_2 and energy, proving to be virtuous systems. This research can give useful indications for farmers, farmer associations, technicians, and stakeholders to improve orchard management efficiency. The net balance approach seems to be an adequate strategy, allowing best estimation of environmental impacts and guiding farmer decisions towards more sustainable alternatives.

Keywords: carbon footprint; RothC model; CO_2 balance; energy balance; sustainability

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1. Introduction

The strong dependence on fossil fuels, and the consequent emissions of greenhouse gases (in particular carbon dioxide and methane), have pushed all productive sectors to adopt new policies aimed at achieving the objectives of environmental, economic, social, and institutional improvement. This has led to the concept of sustainable development, which is a process that binds the protection and the enhancement of natural resources to the economic and social dimensions, so that, in order to meet the needs of current generations, the ability of future ones to satisfy their own needs is not compromised [1].

In the last one hundred years, human activities have led to the increase of atmospheric concentrations of greenhouse gases and other pollutants [2]. The agricultural sector, due to its activities, has produced significant volumes of greenhouse gases, and, thus, contributing to climate change [3–7]. Worldwide, the contribution of the agricultural sector to global emissions is around 20% [3] and these emissions are predominantly generated by nitrous oxide, methane, and carbon dioxide [4,8]. The percentage includes a contribution of 11% from crop and livestock activities within the farm gates, and an additional 9% from related land use [3]. In 2016, the Italian agricultural sector produced about 7.1% of the total emissions, being the third emissive source after energy (81.1%) and industrial processes and product use (IPPU) (7.5%) sectors [9].

Changes in land use have transformed large areas from relatively stable ecosystems in agro-ecosystems that have suddenly changed according to their extensive or intensive management. The introduction of certain intensive agricultural practices, such as drainage, deep soil tillage, and unbalanced fertilizations, have had a major impact on the Earth's carbon pools and fluxes. However, in recent decades, thanks to the growth of community sensitivity towards environmental protection, the agricultural sector has been affected by significant and positive changes. A different consideration of life quality, understood as personal well-being and as an energetic and economic gain, has helped to merge the primary objective of productivity with the interests of land management and environmental protection. Particularly, the optimization and innovation of low impact agronomic techniques, especially concerning soil management, irrigation and mineral nutrition, have allowed the recovery of normal levels of fertility of agro-ecosystems, reducing emissions from the primary sector and improving soil and yield quality [10]. Indeed, rational and sustainable soil management practices can have positive effects on telluric microbial communities that, in turn, are able to influence soil fertility and plant growth. The effects of soil management on the absorption, storage, and partitioning of carbon in soil must also be considered [11].

The estimation of emissions by the agricultural sector is difficult to account for as it is a prevalently widespread pollution, characterized by the extreme variety of environmental features and cultivation management systems. Therefore, several estimation methods have been developed over time and connected to the various cultivation production processes. Bergez et al. [12] proposed a conceptual framework to help evaluate the impacts of agricultural policies on the environment, developed a set of indicators for environmental issues and assessed the issues through four existing approaches (Life Cycle Assessment, Ecosystem Services Analysis, Yield Gap Analysis and Agro-Environmental Indicators). Ponsioen and van der Werf [13] gave an overview of the reasons why it is so difficult to harmonize guidelines for environmental footprints of food and beverage industries. Many aspects of the environmental accounting methodologies used in food production have already been investigated, but the application of environmental indicators in the fruit tree sector is still rare [14,15] and no consensus can be found on which indicator to use [16]. According to Dantsis et al. [17], widely diverging approaches have been adopted to several aspects of the analysis, such as data collection, system delimitation, and the overall objective. Cerutti et al. [16] argued that indicators which consider, at the same time, many aspects of environmental impacts are more useful to address the complexity of agricultural systems. De Backer et al. [18], pointed out that the Life Cycle Assessment has proven to be a valuable tool to address questions on the environmental impact of various agricultural production systems, relating to both the identification of the subsystems that contribute most to the total environmental impact and the comparison of products and processes with the same function [19–26].

In this context, the aim of the present research, carried out within the CarbOnFarm project Life+ ENV/IT/000719, was the analysis of the energy and the environmental sustainability of two orchard systems (kiwifruit and peach orchards) managed according to the integrated production model. For this purpose, the following three environmental assessment methods were taken into consideration and applied to evaluate orchard production systems: Life Cycle Assessment (LCA), Carbon Footprint (CF), and Energy Analysis (EA). In addition to these methodologies, a further effort was made to obtain more accurate and complete information by estimating orchard capacity to store energy and CO_2 in essential components, namely, soil and fruit trees, and comparing biogenic energy and carbon gains with anthropogenic energy consumptions and CO_2 emissions (CF) due to orchard integrated management.

2. Materials and Methods

2.1. Study Area and Orchard Management Systems Description

The study was performed in the Eboli municipality (Campania, Southern Italy, 40°35′ N 15°03′ E) in the extensive plain called "Piana del Sele". This area is characterized by the presence of an agricultural sector particularly developed and diversified in terms of production and occupied area. "La Piana" includes the territory of 11 municipalities. Climate is temperate in winter and mildly warm in summer. The seasonal average temperature is 14 °C and the average annual rainfall is 842 mm (mean 1999–2015).

The experiment was carried out in two integrated orchards (one kiwifruit orchard and one peach orchard) planted on clay soil classified as *Pachic Phaeozems*, according to the system "IUSS WRB '98′" [27]. Integrated production is the most common way to manage fruit orchards in the studied area. It is a farming system that produces high quality crop production using specific protocols, as reported in Decree No. 2722 [28]. The main features of the studied orchard systems are reported in Table 1.

Table 1. Main features of the examined fruit orchard systems: kiwifruit orchard and peach orchard.

Orchard Characteristics	Kiwifruit Orchard	Peach Orchard
Cultivar	Hayward	UFO4
Planting density	889 trees ha^{-1} (4.5 m × 2.5 m)	1482 trees ha^{-1} (4.5 m × 1.5 m)
Training system	pergola	Y-transverse
Trees age (years)	20	15
Cultivation system	Integrated	Integrated
Irrigation	Drip emitter	Drip emitter
Characteristics of support structures and irrigation system	Reinforced concrete poles; main pipe in pvc; dispersing tubes and wings in polyethylene	Chestnut wood poles; main pipe in pvc; dispersing tubes and wingsin polyethylene
Pruning method	Manual	Manual
Pruning residues management	Used as soil mulching	Used as soil mulching
Fertilization	Mineral/annual	Mineral/annual
Soil management	Temporary natural grass cover—Disk harrowing	Temporary natural grass cover—Disk harrowing
Disease control	Conventional products	Conventional products
Harvesting method	Manual	Manual
Average yield (kg ha^{-1} year^{-1})	26,000	26,615

In particular, the two integrated systems, which fall within the same farm, had a 1-hectare extension and were managed in a similar way with differences in: (a) the final product characteristics and value (kiwifruits vs. peaches); (b) the training system (pergola vs. ypsilon-transverse); (c) the planting distances (4.5 m × 2.5 m vs. 4.5 m × 1.5 m); (d) the duration of the production cycle (20 years vs. 15 years, for kiwifruit and peach orchards, respectively); (e) the support structures used in the field (concrete poles vs. chestnut poles).

2.2. The Environmental Analysis Assumptions

An in-depth analysis was performed using the LCA approach, according to ISO 14040-44 [29,30]. Each of the three analyses (EA, LCA, CF) was articulated in the following four interrelated phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation.

Following suggestions from Pergola et al. [31], Cerutti et al. [32], and Milà i Canals et al. [21], the whole orchard life cycle was considered. Therefore, the reference period of the analyses was set at 15 years for the peach orchard and 20 years for the kiwifruit orchard (the average productive cycle for these species). The following four main farming phases were taken into account: soil preparation and trees plantation, tree growth, full production, and trees explant.

The system boundaries (Figure 1) were from the raw materials extraction for inputs and machines up to the farm gate (kiwifruit and peach harvesting). All inputs (fuel, lubricants, fertilizers, pest control products, water, materials for setting up the irrigation system, etc.) were included, considering their manufacturing processes. The transportation of inputs was excluded from the analyses, due to incomplete data. Likewise, the environmental impact of manure production was excluded, due to the lack of appropriate information in the databases.

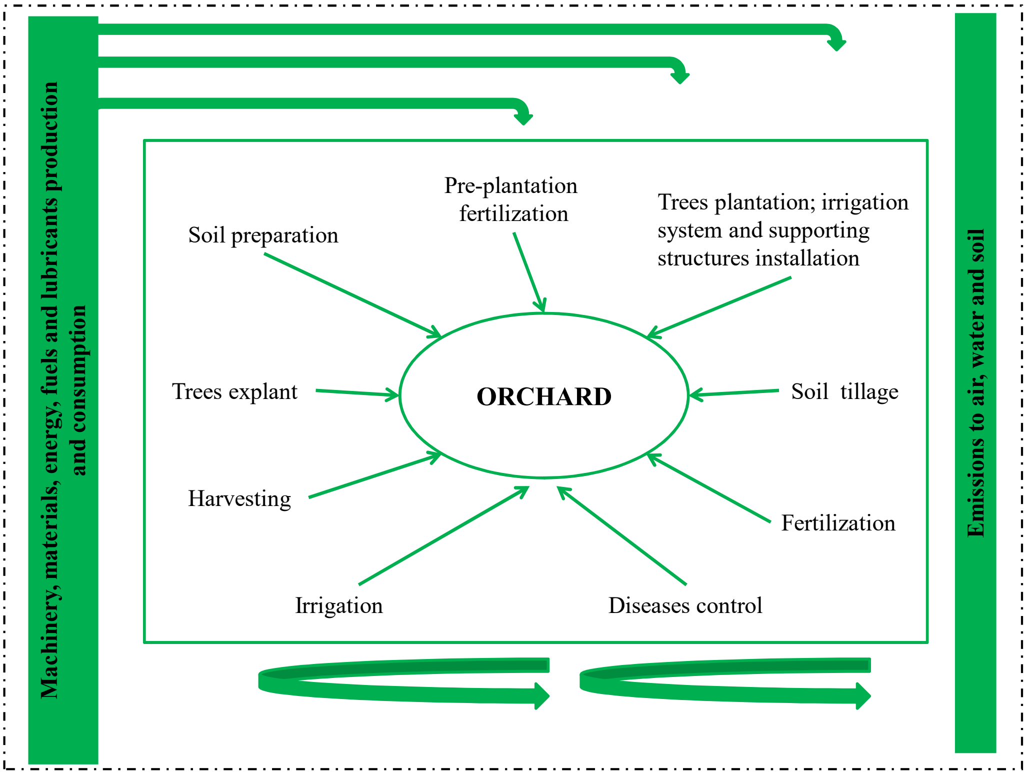

Figure 1. System boundaries for Life Cycle Assessment (LCA), Carbon Footprint (CF) and Energy Analysis (EA).

The functional unit (FU) in LCA is the reference to which the inputs and outputs of the inventory are related, allowing comparison between systems or alternatives [29,30]. The FU of the investigated orchards was the production of kiwifruits and peaches. Therefore, the basis for the systems comparison, named the FU of the service delivered, was defined as the production of 1 kg of harvested fruits. The cultivation of one hectare of farm land was chosen in order to improve the interpretation of the environmental results [16,31,33].

Data associated to the studied orchards (quantities of machinery, fuel, lubricants, and other items) were collected in situ using a data collection sheet. This information was gathered from farmers. The following farming operations were taken into account: plantation (soil preparation, pre-plantation fertilization, trees plantation), soil tillage, fertilization, disease control, irrigation, harvesting, and explant of fruit trees at the end of their life cycles. Farm inputs, used in the examined orchard systems during the reference period, are reported in Table 2.

Table 2. Farm inputs used in the examined fruit orchard systems during the whole production cycle (20 and 15 years for kiwifruit and peach orchards, respectively).

	Kiwifruit Orchard	**Peach Orchard**
Fertilizers (kg ha^{-1})		
Manure	3000	3000
Calcium nitrate	2160	1560
Potassium nitrate	1008	-
Urea	2952	1456
NPK	2160	1560
Sequelane	1080	-
Chemicals (kg ha^{-1})		
Copperic fungicide	70	-
Ziram	-	111
Imidacloprid	-	8.8
Tebuconazole	-	8.9
Sulfur	-	4.8
Thiophanate methyl	-	6.9
Mineral oil	-	31
Penconazole	-	12.4
Thiamethoxam	-	6.9
Azocyclotin	-	13.8
Sorbitan mono oleate	-	5.2
Glyphosate	85	63
Human labour (h ha^{-1})	12,506	10,433
Machinery and farm tools (h ha^{-1})	1142	776
Diesel (kg ha^{-1})	5567	5115
Lubricants (kg ha^{-1})	81.39	63.25

In this study, priority was given to primary data in terms of input material typologies and amounts used. Additionally, as a standard practice in LCA, the active ingredient of each product, the quantity of machines utilized, and the amount of fuel and lubricants consumed were calculated for each operation taken into account and used in the analysis to estimate direct and indirect emissions.

Direct emissions from fuel and lubricants were taken from SimaPro's LCI databases. Referring to fertilizers, as explained in another similar research [31], an entire mineral balance was not undertaken to estimate emissions from them. It is often difficult to derive exact rates of N released to the air and water, because emission rates can vary greatly, depending on soil type, climatic conditions, and agricultural management practices. However, nitrogen emissions from cultivation were accounted for, according to Brentrup et al. [34] and IPCC [35]. N leaching and run-off, as N loss processes, were not considered because the analyzed orchards fall in an area where leaching/run-off does not occur. In addition, the difference between precipitation in the rainy season and the potential evaporation in the same period is not greater than soil water holding capacity. Moreover, drip irrigation was employed within the analyzed orchards as water application method [35].

CO_2 emissions from urea was estimated, taking into account the annual fertilizer amount and the respective emission factor (0.20), which is the equivalent carbon content of urea on an atomic weight basis (20% for $CO(NH_2)_2$) [35]. P leaching to the groundwater was not estimated in this study because the same considerations made for N leaching were applied. P run-off to surface water and P emissions through erosion to surface waters were not considered because the orchard systems are planted on flat lands. As in Milà i Canals et al. [21] and Pergola et al. [31] emissions of synthetic pesticides to air, surface water, groundwater and soil were estimated according to the methodology suggested by Hauschild [36].

With a view to life cycle analysis, indirect emissions refer to both: (a) the consumption of raw materials, auxiliary and technical materials; (b) emissions of substances during production, transport and disposal of the various inputs used during the analysis. Therefore, such secondary data were extrapolated from international databases of scientific importance and reliability, like Ecoinvent 3 [37]. In particular, this was done for the following: the production of diesel, lubricants, fertilizers and pesticides used in the investigated systems, including the accounting of the resulting emissions; the construction of agricultural vehicles and fixed structures (irrigation system and supporting structures).

Referring to diesel and lubricants, the fuel consumption model included the transportation of the product from the refinery to the end user. To this end, European Commission data [38] were considered, indicating, in summary, emissions equal to 0.714 kg CO_2 eq for the production and transport of 1 kg fuel.

The environmental impact assessment was carried out using SimaPro 8.04 software, with the problem oriented LCA method, developed by the Institute of Environmental Sciences of the University of Leiden [39]. The impact categories considered in the present analysis were the same commonly used in agricultural LCAs: abiotic depletion (AD), global warming potential (GWP) or climate change, photochemical oxidation (PO), air acidification (AA), and eutrophication (EU). Furthermore, the impact assessment was performed following a mid-point approach by using equivalent indicators (specific for the impact categories considered) to express the LCA results as characterization values. In order to assess the contribution of each impact category on the overall environmental problem, "Normalization" of the characterization results was done using as "Normal" value the region "Europe 25" [40].

2.3. Estimation of C–CO_2 Balance

The C–CO_2 balance was calculated as the difference between the total C–CO_2 storage in the two analyzed fruit tree systems at the end of their life cycles (20 years for the kiwifruit orchard and 15 years for the peach orchard) and their CFs.

For both the compared systems, the total C–CO_2 storage was calculated as the sum of CO_2 sequestered in the soil and in the fruit trees at the end of their corresponding life cycles. The first was estimated across the RothC-26.3 model, which is used to predict changes over time in soil organic carbon stocks within agricultural lands, according to soil type, temperature, moisture content, and plant cover [41–43]. In order to run the model, climatic data, soil data, and land use and management data were acquired. Particularly, a time series of climatic data (1999–2015), recorded by a meteorological station representative of the survey area, was elaborated to provide input data for the RothC model. Clay content, total and particulate organic matter, and mineral associated fraction were measured on soil samples taken in Spring 2014 from the two orchard systems at 0.30 m depth [44,45]. Information on land use and management (soil cover, monthly input of crop residues and farmyard manure, residue quality factor) was acquired by means of questionnaires addressed to farm owners, inspections and field measurements, and literature data. The initial soil carbon content (year 0) of the orchard systems was calculated using the RothC model and the known input following an iterative and retrospective approach.

The assessment of CO_2 sequestered in the aboveground permanent structures of the kiwifruit and peach trees was performed following a derivative approach, consisting of the destructive measurements of representative trees coming from other orchards at the end of their life cycles, characterized by the same training system and planting density of the experimental groves. Particularly, at the explant, 5 trees per each orchard were cut at the base of the trunk. Then, each tree was divided into its different wooden structures (trunk, branches, twigs, suckers) which were weighed directly on the field by means of a portable balance for fresh weight data. From each wooden structure a sample of about 10% of its fresh total weight was taken, labelled, moved to the laboratory and put into a forced-draft oven at 65 °C for 6 days. After drying, plant samples were weighed again to calculate their dry matter content. These values were applied to the biomass fresh weight in order to calculate the total dry weight of the standing plants. The dry samples were then crushed into fine powder (<200 mesh). Fifty mg of each sample was weighed in ceramic boats and analyzed by means of the Sulphur and Carbon Analyzer LECO-SC 144.

The amount of CO_2 sequestered in the different permanent structures was calculated using the following relation:

$$CO_2 = FWx \times (DMx\%/100) \times (C\%x/100) \times K_{CO2}$$

where for the single wooden part, indicated as x,

CO_2 = CO_2 equivalents expressed in grams
FWx = fresh weight expressed in grams
DM%x = percentage of dry matter
C%x = percentage of carbon
K_{CO2} = 3.67 stoichiometric coefficient (from C to CO_2).

The CO_2 sequestered in the whole aboveground part of the tree was calculated by summing the CO_2 fixed in the different wooden structures.

The CO_2 sequestered in the whole kiwifruit and peach tree (aboveground part + belowground part) was calculated using the mean value of the aboveground part to belowground part ratio (0.45 and 0.58 for peach and kiwifruit tree, respectively) found in the available literature on fruit orchards [46–48].

Finally, data were normalized according to the planting density in order to calculate the CO_2 sequestered per hectare (CO_2 ton ha^{-1}). These last data were then divided for the respective years of the orchard life cycle, according to a linear distribution procedure, to assess the CO_2 sequestered, on average, every year.

The above-described procedure allowed calculation of the CO_2 stock variations directly linked to the fruit trees. Roots and epigean part decay (i.e., decomposing fine roots, leaf turnover, natural grass cover and pruning material recycled in the orchard) are capitalized into the soil organic matter along the cultivation years, while carbon included in fruits shows a short life under organic form (except for the negligible carbon amount due to the wooden fruit endocarp), so the latter were not considered in the analysis.

Referring to CF, ISO 14,067 [49] defines CF as the sum of greenhouse gas emissions (carbon dioxide: CO_2; methane: CH_4; nitrous oxide: N_2O; ozone: O_3; the halocarbons: CFC, HCFC, HFC) and removals in a product system expressed as CO_2 equivalents, and based on a life cycle assessment using the single impact category of climate change [50]. Therefore, CF measures the total amount of greenhouse gas emissions, both direct (on-site) and indirect (off-site), caused by an activity or accumulated during the production and supply chain of a product throughout its 'life cycle' [51,52]. Generally, the total amount of greenhouse gas emissions is expressed in the mass unit, which is referred to the CO_2, because it is the most important gas affecting global warming. Concerning global warming, CH_4, N_2O, HFC, PFC, and SF6 are normalized to their global warming potentials, according to the United Nations Framework of Convention on Climate Change [35].

In accordance with the LCA methodology and the CF guidelines [49], in this research the CF was performed using 1 kg of harvested product and 1 hectare of cultivation land as functional unit and identifying the same system boundary "from cradle to gate" previously seen (Figure 1). Direct and embodied emissions were accounted for as seen in the previous paragraph.

2.4. Energy Balance

The energy analysis/balance represents, in the same way as the environmental analysis, one of the tools used to assess the sustainability of agricultural activities. EA consists of observing, appreciating, and measuring energy flows within a system. Following Namdari et al. [53], the EA method was used to calculate the energy involved in the production of 1 kg of kiwifruits and peaches. To combine the EA results with those coming from LCA, the analysis was performed with the same system boundary and the same life cycle inventory described for LCA. Collected data covered the duration of each operation and the quantities of each input (machinery, fuel, fertilizers, labor, and so on). Energy values of unit inputs were given in mega joules (MJ) by multiplying each input by its own coefficient of equivalent energy factors taken from the literature [54–57]. In order to calculate machinery energy (ME), the following formula was used [58]:

$$\mathrm{ME} = [(Eeq \times G/T)] \times H$$

where

Eeq = machinery energy equivalent (MJ kg^{-1})
G = weight of machines (kg)
T = economic life of machines (h)
H = numbers of hours the machine took to carry out the various operations (h).

Energy consumption for machinery maintenance was estimated as a percentage of energy in manufacturing and materials (23% for tractors; 30% for tillage machines) [59].

The energy input was examined as direct and embodied forms, and non-renewable/renewable energies. Direct energy included human labor, diesel fuel and lubricants used in the two orchards described; whilst embodied energy covered machinery and maintenance, chemicals, fertilizers, manure, and plastic materials. Non-renewable energy consists of diesel, lubricants, chemicals, electricity, fertilizers and machinery energies. Renewable energy includes human labor, plants, manure, and water for irrigation [53].

The energy output of the examined orchard systems was calculated as the sum of energy gained by the soil and energy permanently fixed in the fruit trees at the end of the orchard life cycle. The former was estimated by multiplying the quantity of C fixed in the soil (at year 0, at the last life cycle year, and the variation) by its coefficient of equivalent energy factor (34 MJ kg^{-1}) taken from Rovira and Henriques [60]. The latter was determined by multiplying the dry matter of the studied orchard trees by their coefficient of equivalent energy factor (14.64 MJ kg^{-1}), indicated by Volpi [57].

3. Results and Discussion

3.1. Environmental Impacts

Data processing per kg of harvested product per year, shown in Table 3, highlighted the less environmental sustainability of the kiwifruit orchard. In particular, the production of 1 kg of kiwifruit caused a consumption of resources equal to 5.38 $\times 10^{-7}$ in terms of kg of Sb eq, and emissions equal to 1.45 $\times$ 10^{-1} kg of CO_2 eq; 7.69 $\times$ 10^{-9} kg of CFC-11 eq; 1.95 $\times$ 10^{-5} kg of C_2H_4 eq; 1.67 $\times$ 10^{-3} kg of SO_2 eq and 5.86 $\times$ 10^{-4} kg of $PO_4{}^{3-}$ eq.

Table 3. Life cycle impacts per kg per year of harvested product from the different fruit orchard systems (kiwifruit orchard and peach orchard).

Impact Category	Unit (kg^{-1})	Kiwifruit Orchard	Peach Orchard
Abiotic depletion	kg Sb eq	0.000000538	0.000000343
Global warming (GWP100a)	kg CO_2 eq	0.144646154	0.124476173
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000000000	0.000000007
Photochemical oxidation	kg C_2H_4 eq	0.000019519	0.000019438
Acidification	kg SO_2 eq	0.001674981	0.001551205
Eutrophication	kg $PO_4{}^{3-}$ eq	0.000586192	0.000422443

On the contrary, the production of 1 kg of peaches caused minor impacts, especially with reference to global warming (0.124 kg of CO_2 eq compared to 0.145 kg emitted for the production of 1 kg of kiwifruit). The greatest impact of kiwifruit cultivation was more evident if data were normalized (Figure 2).

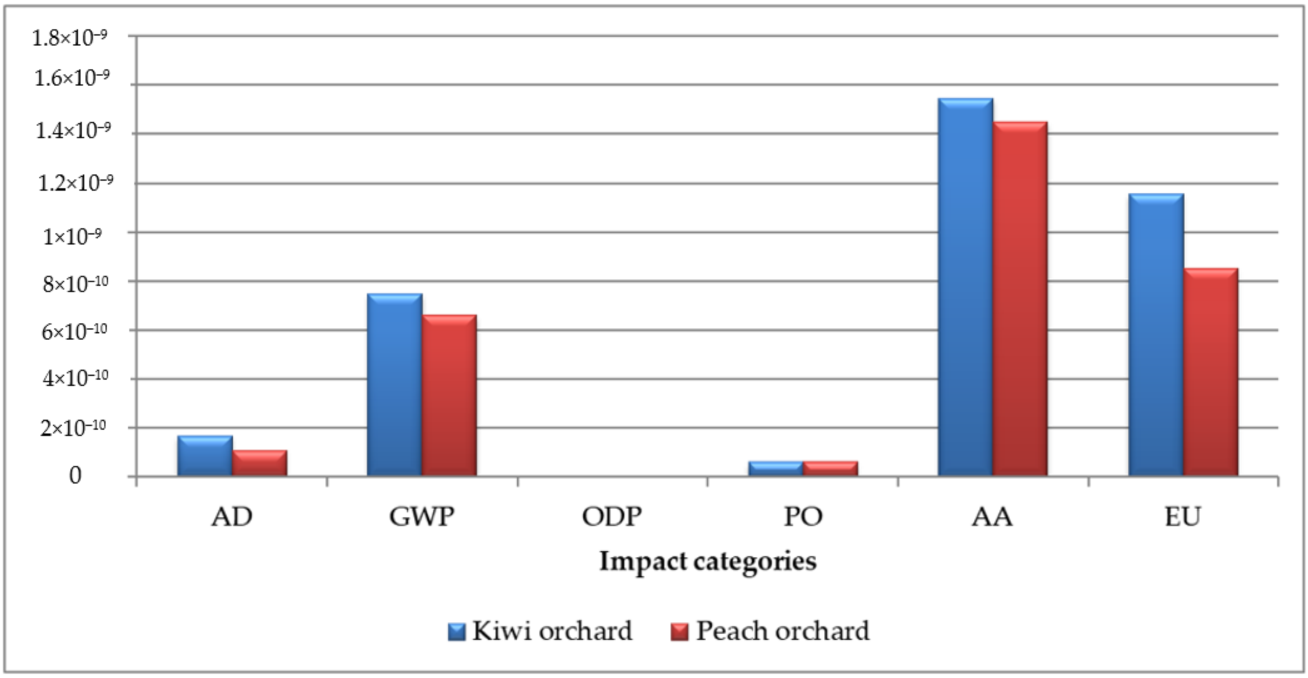

Figure 2. Normalization of the impact categories of the examined fruit orchard systems (AD: Abiotic depletion; GWP: Global warming potential; ODP: Ozone layer depletion; PO: Photochemical oxidation; AA: Air Acidification; EU: Eutrophication).

In both orchard systems the greatest impacts were charged to the following categories: acidification, eutrophication, and global warming potential (Figure 2). Analyzing data for each cultivation operation, the most impactful operation within the kiwifruit orchard was the fertilization (49%), and, specifically, the production of the different fertilizers used, followed by soil preparation (12%), plantation (9%) (due to the supporting structures), and disease control (7.5%). These operations caused mainly acidification, eutrophication, and global warming (Figure 3). Similarly, the most impactful operations in the peach orchard were: fertilization (37%), soil preparation (19%) and disease control (16%), mainly due to direct emissions. Fertilization was one of the most impactful operations in other studies too [61], especially in horticultural research [62–66].

Referring to soil preparation, trees plantation phase, irrigation system and supporting structures installation in the peach orchard had lower impacts than in the kiwifruit orchard, mainly due to the lower quantity of structures used for tree planting. Indeed, in the peach orchard wooden poles (whose production was less impactful) were used instead of concrete ones, as occurred in the kiwifruit orchard. Moreover, the pergola training system, used in the kiwifruit orchard, required greater quantities of steel than those employed within the peach orchard. The analysis of the individual farm operation contributions on the different impact categories is shown in Figure 4.

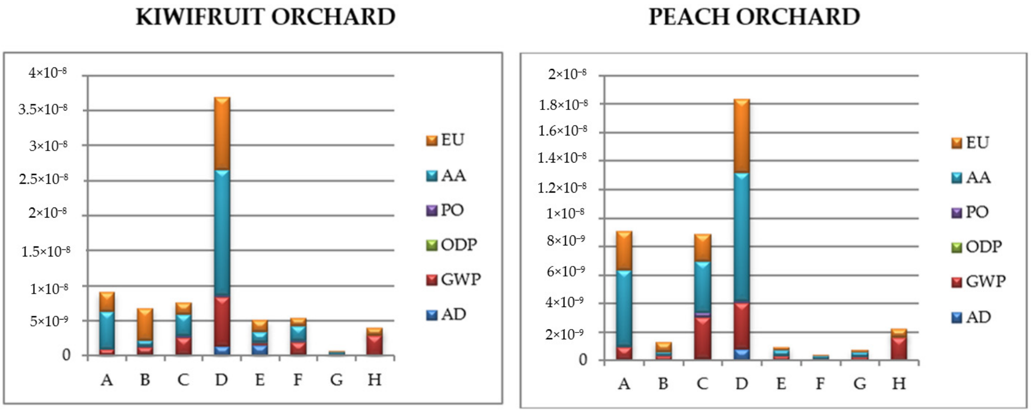

Figure 3. Contribution of the agricultural operations to the impact categories per kg of product obtained per year from each fruit orchard system. Normalization values (A: Soil preparation; B: Plantation, irrigation system and supporting structures installation; C: Weed control and soil tillage; D: Fertilization; E: Diseases control; F: Harvesting; G: Trees explants; H: Crop residues; EU: Eutrophication; AA: Air Acidification; PO: Photochemical oxidation; ODP: Ozone layer depletion; GWP: Global warming potential; AD: Abiotic depletion).

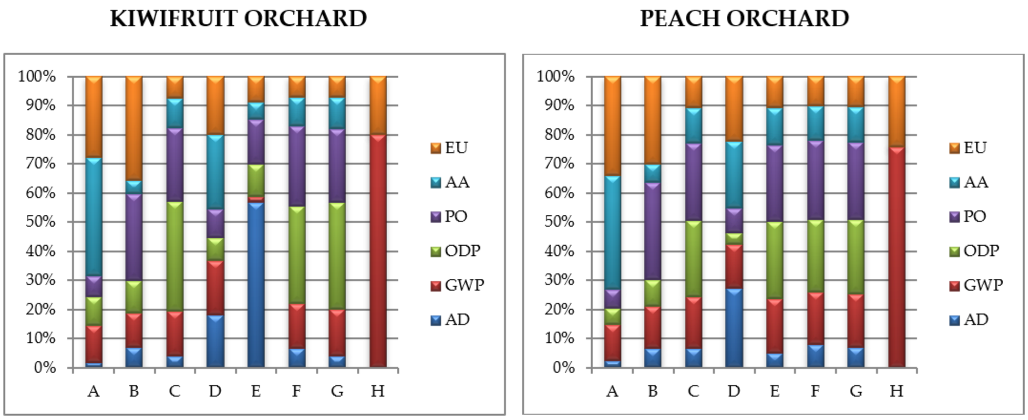

Figure 4. Percentage distribution of environmental impacts by agricultural operation (A: Soil preparation; B: Plantation, irrigation system and supporting structures installation; C: Weed control and soil tillage; D: Fertilization; E: Diseases control; F: Harvesting; G: Trees explants; H: Crop residues; EU: Eutrophication; AA: Air Acidification; PO: Photochemical oxidation; ODP: Ozone layer depletion; GWP: Global warming potential; AD: Abiotic depletion).

Data highlighted that in the kiwifruit orchard, water eutrophication was mainly caused by soil preparation and by the planting phase and air acidification by soil preparation and fertilization. Photochemical oxidation and ozone depletion were two widespread problems produced by the emissions of C_2H_4 eq and CFC-11 eq, respectively, and, therefore, they were more generally caused by all farm operations. Conversely, global warming depended essentially on the emission of nitrous oxide from the decomposition of crop residues (pruning material and grass cover). Disease control contribution to global warming was minimal, but really important in resource depletion.

In the peach orchard, water eutrophication was mainly caused by soil preparation and planting phase and air acidification by soil preparation and fertilization. Photochemical oxidation and ozone depletion were essentially caused by disease control, while soil preparation, planting and fertilization did not significantly affect these impact categories. As observed for the kiwi orchard system, global warming was essentially caused by the emission of nitrous oxide coming from the decomposition of crop residues; more generally, it was caused in equal measure by all the agricultural operations. Finally, resource depletion was essentially produced by disease control and fertilization (Figure 4).

3.2. Carbon Footprint Focus

In order to deepen the LCA analysis and highlight the differences between the two orchard systems under study, the direct and indirect emissions of the individual production factors responsible for the different impacts were calculated. The peach orchard cultivation yearly emitted into the atmosphere, at hectare level, about 3313 kg of CO_2 eq, 2186 kg of direct emissions (about 66% of the total) and 1126 kg of indirect emissions, related to the production and transport of the various factors considered (about 34% of the total). On the contrary, in the kiwifruit orchard, annual emissions of greenhouse gases amounted to about 3761 kg of CO_2 eq; 2313 kg as direct emissions (61.50%) and 1448 kg (38.50%) as indirect ones. With regard to direct emissions, in both orchards, annually, the main sources of such emissions came from fuel combustion, release of nitrous oxide linked to crop residues decomposition and to the distribution in the field of nitrogenous fertilizers. In particular, the production of 1 kg of peaches and kiwifruit involved a direct emission of CO_2 eq equal to 0.08 and 0.09 kg, respectively.

Indirect emissions were greater within the kiwifruit orchard for almost all the factors analyzed (agricultural machinery and tools, irrigation system and supporting structures, fertilizers, plastic) except for pesticides and fuels. The major differences between the two orchards were related to the support structures (steel and cement used in the kiwifruit orchard against wood in the peach orchard) and fertilizers distributed (the longer duration of the production cycle of the kiwi orchard implied a greater consumption of fertilizing principles). As previously mentioned, pesticides use in the kiwifruit orchard was less impactful, due to the exclusive use of copper sulphate as means of disease control. Due to high sensibility from the phytosanitary point of view, more products of different chemical nature were used in the peach orchard, depending on the phenological stage of the plant (Ziram, Topas, Tiovit Jet, etc.). Ultimately, the production of 1 kg of peaches and kiwifruit caused indirect emissions of 0.04 and 0.06 kg of CO_2 eq, respectively. Results obtained from this research were in line with other studies available in the literature. Particularly, CO_2 eq emissions per kg of kiwifruit (0.145) were similar to those found in pears (0.140) by Liu et al. [67]. CO_2 eq emissions per kg of peaches (0.124) were similar to those found by Milà i Canals et al. [21] for the cultivation of apples (0.120), and by Pergola et al. [68] in conventional cultivation of lemons (0.12) and oranges (0.13). The analyzed productions were less impactful than those found by Ingrao at al. (0.23) for an integrated peach orchard and for a biodynamic apricot orchard (0.42 kg of CO_2 eq kg apricots^{-1}) grown under greenhouse cultivation [69]. On the other hand, this plant growing system can be strongly impactful, representing around 90% of the total impacts [69]. Therefore, the different emission calculating methods and system boundaries, the different productivities of the analyzed systems and their life spans (entire production cycle *versus* 1 year of cultivation) made our results more or less accord with literature data.

3.3. Energy Analysis

Energy consumption per unit of harvested product (1 kg) is reported in Table 4.

The production of 1 kg of kiwifruit required 1.32 MJ of energy, against 1.56 MJ required for peach production. These energy values were higher than others found in the literature for apricots. In particular, Gezer et al. [70] stated that the conventional production of 1 kg of apricots in Turkey required 1.20 MJ of energy, while Esengun et al. [71] reported energy requests ranging from 1.04 to 1.08 MJ kg^{-1}, In the same region, Gündoğmuş [72] stated that conventional apricot production required 1.68 MJ kg^{-1}, while organic apricot production required 1.11 MJ kg^{-1}. On the contrary, Pergola et al. [31] found that apricot production required an average of 3 MJ kg^{-1}. Such high energy consumption, if compared to results obtained by this study, was due to the use of irrigation pipes in galvanized steel and to the lower productivity of the apricot orchard considered. As a matter of fact, the higher yields, as in the present study, corresponded to lower impacts and energy consumption.

Table 4. Energy consumption per kg of product from the examined fruit orchard systems (kiwifruit and peach orchards) in the whole production cycle (20 and 15 years for kiwifruit and peach orchards, respectively).

Agricultural Operation	Kiwifruit Orchard (MJ kg^{-1})	Peach Orchard (MJ kg^{-1})
Soil preparation	0.05	0.06
Trees plantation, irrigation system and supporting structures installation	0.23	0.17
Pruning and other manual operations	0.05	0.04
Weed control and soil tillage	0.32	0.08
Fertilization	0.36	0.29
Diseases control	0.06	0.66
Harvesting	0.21	0.23
Trees explant	0.03	0.04
Total energy input (TEI)	1.32	1.56

In detail, the cultivation of the analyzed kiwifruit orchard, from plantation to the explant, required 687,914 MJ of energy and the yearly value was 34,396 MJ ha^{-1} (Table 5).

Table 5. Energy consumption per hectare (MJ ha^{-1}) from the examined fruit orchard systems (kiwifruit and peach orchards) in the whole production cycle (20 and 15 years for kiwifruit and peach orchards, respectively).

Agricultural Operation	Kiwifruit Orchard Total	Peach Orchard Total	Kiwifruit Orchard Yearly	Peach Orchard Yearly	Kiwifruit Orchard %	Peach Orchard %	Kiwifruit Orchard More Energivorous Factor	Peach Orchard More Energivorous Factor
Soil preparation	23,950	17,498	1198	1167	3%	4%	-	-
Trees plantation, irrigation system and supporting structures installation	120,699	51,116	6035	3408	18%	11%	PE pipes, concrete poles, steel wire	PE pipes and chestnut poles
Pruning and other manual operations	28,392	11,357	1420	757	4%	2%	-	-
Weed control and soil tillage	168,889	23,988	8444	1599	25%	5%	-	-
Fertilization	189,294	87,582	9465	5839	28%	19%	Fertilizers production	Fertilizers production
Diseases control	32,227	197,356	1611	13,157	5%	42%	Fuel	Fuel
Harvesting	108,707	67,984	5435	4532	16%	15%	Fuel	Fuel
Trees explant	15,756	11,488	788	766	2%	2%	-	-
Total energy input (TEI)	687,914	468,370	34,396	31,225	100%	100%	-	-

The peach orchard required 468,370 MJ ha^{-1} at the end of the cycle and 31,225 MJ ha^{-1} per year (Table 5). In a long-term analysis, as conducted in this research, the highest energy demand found for the kiwifruit orchard was essentially due to the longer duration of its production cycle (20 years vs. 15 year of the peach orchard).

Fertilization (28%), weed control and soil tillage (25%), trees plantation (18%), and harvesting (16%), were the farm operations that required more energy within the kiwifruit orchard (Table 5). In particular, this energy consumption was essentially attributable to the production of fertilizers, fuels and lubricants, and supporting structures. Indeed, processing data for production factors (Figure 5) showed that diesel and lubricants (38%), and fertilizers (28%) were the items that required more energy. At the same time, as reported in other studies [24,73,74], human labor was the factor with the lowest energy requirement (4%) (Figure 5).

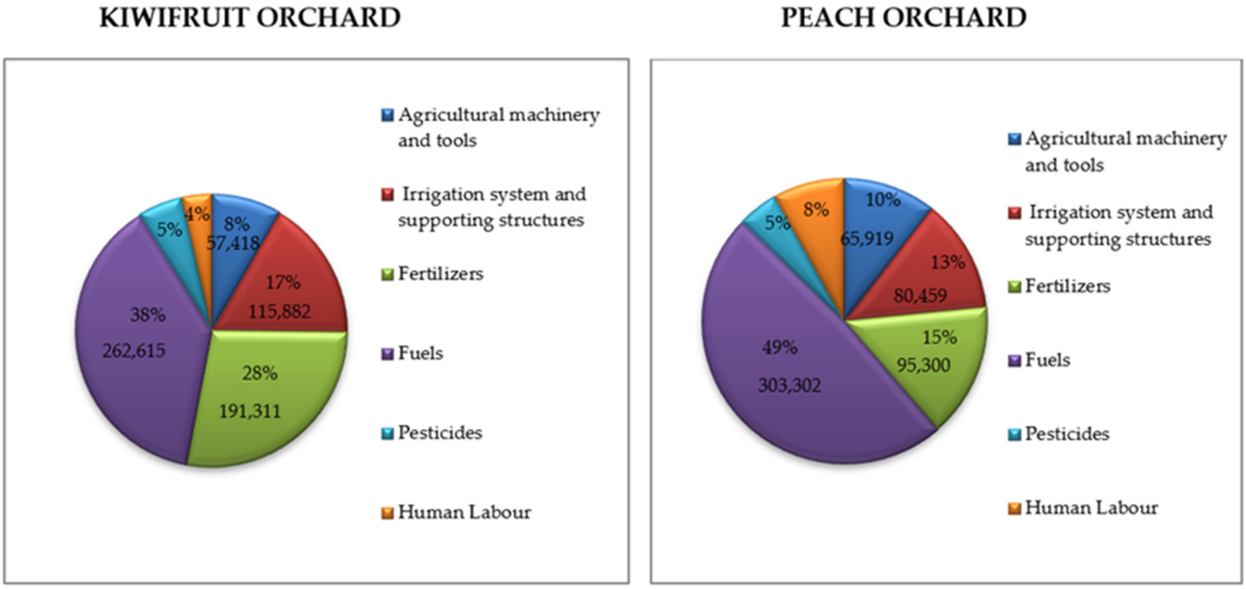

Figure 5. Percentage distribution of energy consumption by production factors.

Unlike the kiwifruit orchard, disease control (42%) and fertilization (19%), followed by plantation (15%) and harvesting (11%) were the farm operations requiring more energy within the peach orchard. In particular, the factors determining this energy consumption were fuels and fertilizer production and, secondly, supporting structures. Ultimately, as already seen previously in the environmental analysis, the great phytosanitary sensitivity of the peach orchard made disease control the most impactful operation, even in terms of energy consumption (Table 5).

The items that required more energy in the peach orchard were diesel oil and lubricants (49%), fertilizers (15%), and fixed structures (13%). As seen in the kiwifruit orchard, the factor requiring the lowest energy was human labor (5%) (Figure 5). In short, the percentage distribution of energy consumption for the various production factors showed that the two orchards differed essentially for fuel, which, in the peach orchard, represented about 49% of the total energy input, and in the kiwifruit orchard represented only 38%. This was due to the greatest use of agricultural machinery within the peach orchard to carry out anti-parasitic treatments. Even the fertilizers item (mineral fertilizers and manure) showed strong discrepancies between the systems. In the peach orchard, fertilizers represented about 19% of the total, while in the kiwifruit orchard they represented about 28%. This was primarily due to the different mineral requirements of the two crops and, secondly, to the different durations of the production cycles.

Furthermore, the energy analysis highlighted the different forms of energy introduced into the two orchards: direct and indirect, renewable and non-renewable. The peach orchard used a little more direct energy (relative to fuel and human labor) than the embodied energy (structures, fertilizers, machines, etc.) (248,236 vs. 220,134 MJ ha^{-1}). On the contrary, the kiwifruit orchard used more incorporated energy (60%) than direct energy (400,910 vs. 287,002 MJ ha^{-1}). This was in accordance with what has already reported; in the kiwifruit orchard, the quantities of energy incorporated in the support structures were greater than those assessed within the peach orchard. Moreover, the analyzed orchards essentially used non-renewable energy (connected to structures, fertilizers, machines, fuels, lubricants and synthetic products). In fact, the renewable energy (related to human labor and manure) introduced into the two systems was about 5.7% in the peach orchard and 4.0% in the kiwi orchard.

3.4. CO_2 and Energy Balance per Hectare

Data of organic carbon sequestered by the systems under observation, expressed as CO_2 ha^{-1}, are reported in Table 6. The peach orchard, trained to Y-transverse, in the 15-year period sequestered, on average, 329 tons of CO_2 ha^{-1}, of which 153 tons of CO_2 ha^{-1} was in tree structures (above-ground part plus below-ground part) and 176 tons of CO_2 ha^{-1} in the soil. The mean annual CO_2 sequestration by the peach orchard was equal to 22 tons CO_2 ha^{-1} (12 tons of CO_2 ha^{-1} in soil). The kiwifruit orchard, trained to "pergola", in 20 years sequestered 425 tons of CO_2 ha^{-1} in total, 56% of which was in tree structures (Table 6).

Table 6. Total C–CO_2 sequestered in the soil and in the permanent structures in the whole production cycle (20 and 15 years for kiwifruit and peach orchards, respectively) and CO_2 balance of the two examined orchard systems. Values are expressed as ton of CO_2 eq per ha. Negative values indicate a CO_2 gain by the system.

	Kiwifruit Orchard		**Peach Orchard**
soil (year 0)	79	soil (year 0)	79
soil (year 20)	268	soil (year 15)	256
Soil C–CO_2 variation (20-0 year)	189	Soil C–CO_2 variation (15-0 year)	7
A—above-ground stock (permanent structures)	149	A—above-ground stock (permanent structures)	105
B—below-ground stock (root biomass)	87	B—below-ground stock (root biomass)	48
C-CO_2 storage in trees (A + B)	236	C-CO_2 storage in trees (A + B)	153
Total C–CO_2 stock (soil + trees)	425	Total C–CO_2 stock (soil + trees)	330
Global warming (GWP100)	75	Global warming (GWP100)	50
CO_2 balance	−350	CO_2 balance	−280

The comparison of the two orchard systems indicated that the kiwifruit orchard was able to fix, at the end of its reference period (20 years), a higher total amount of CO_2 than the peach orchard, especially when referring to the percentage sequestered in above-ground and below-ground parts (Table 6). This was essentially due to the "pergola" training system, which allowed trees to have greater growth and, consequently, to store more CO_2.

The CO_2 balance, calculated as the difference between the global warming impact category and the total C–CO_2 eq fixed in the studied systems (soil plus tree structures), only as carbon, is reported in Table 6. Both analyzed orchards seemed to be environmentally sustainable; despite their management releasing CO_2 eq (75 and 50 tons of CO_2 ha^{-1} for kiwifruit and peach orchards, respectively), their CO_2 storing capacity made them more virtuous than other orchard systems. As reported by Pergola et al. [31], who compared, in 2016, two integrated apricot systems and a biodynamic one, integrated systems were inefficient systems per land unit, emitting more CO_2 eq than that fixed (38.9 tons ha^{-1} the Ninfa and 12.5 tons ha^{-1} the Rubis). Otherwise, the biodynamic system, despite the high release of CO_2 eq (124.6 tons), due to the greenhouse construction, showed a satisfying capacity of storing CO_2 (204.3 tons) with a favorable gain of nearly 80 tons of CO_2 ha^{-1}. Anyway, such results confirmed that soil carbon sequestration is an important and immediate sink for removing atmospheric carbon dioxide and slowing global warming [75].

Data of energy sequestered by the orchard systems, expressed as GJ ha^{-1}, are reported in Table 7.

In accordance with what has already been reported, the kiwifruit orchard, after 20 years of cultivation, gained more energy than the peach orchard, especially in tree structures (1810 GJ ha^{-1} on a total of 3559 GJ ha^{-1}). On the other hand, taking into account the energy balance (as the difference between the total energy input and the total energy stock in the studied systems), both systems seemed to gain energy. In detail, the kiwifruit orchard showed an energy gain of 2871 GJ ha^{-1} (144 GJ ha^{-1} per year), while the gain made by the peach orchard was equal to 2338 GJ ha^{-1} (156 GJ ha^{-1} per year) (Table 7).

Table 7. Energy incorporated in the soil and in permanent structures in the whole production cycle (20 and 15 years for kiwifruit and peach orchards, respectively) and energy balance of the examined orchard systems. Values are expressed as GJ ha^{-1}. Negative values indicate an energy gain by the system.

	Kiwifruit Orchard		Peach Orchard
soil (year 0)	731	soil (year 0)	736
soil (year 20)	2480	soil (year 15)	2368
Soil Energy variation (20-0 year)	1749	Soil Energy variation (15-0 year)	1632
A—above ground stock (permanent structures)	1143	A—above ground stock (permanent structures)	805
B—below ground stock (root biomass)	667	B—below ground stock (root biomass)	368
Energy storage in trees (A + B)	1810	Energy storage in trees (A + B)	1173
Total Energy stock (soil + trees)	3559	Total Energy stock (soil + trees)	2805
Total energy input	688	Total energy input	468
Energy balance	−2871	Energy balance	−2337

4. Conclusions

The present research was conducted to provide a useful contribution to broadening the scientific literature on the estimation and comparison of the environmental and energy impacts of fruit orchards managed according to the widespread integrated cultivation systems.

The obtained results can be useful for farmers, farmer associations, technicians and stakeholders to identify agricultural operations and inputs which are the most critical for the environment and to steer them towards the most opportune crop management alternatives. The use of more energy-efficient and environmentally-efficient soil management systems/machines, such as roller crimpers to manage cover crops in orchards, and of soil organic matter improvers, such as compost or compost teas self-produced on farms, both lead to the reduction of climate-altering gas emissions and costs, and to low inputs of synthetic fertilizers.

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