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Adaptation of Mediterranean Olive Groves to Climate Change through Sustainable Cultivation Practices

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Abstract: Olive cultivation is considered as one of the most significant agricultural activities in Greece, from a financial, social, and ecological point of view. Intensive cultivation practices in combination with the Mediterranean climate, lead to depletion of soil organic matter, erosion, desertification, and degradation of water resources. This paper describes sustainable olive crop management practices that were comparatively applied in 120 olive groves in Greece for 5 years with the participation of three farmers groups. Organic materials recycled in the olive groves during the present study were valuable sources of carbon, nitrogen, phosphorus, and potassium. Carbon content was highest in pruning residue (53.8–54.2%) while all materials studied were considered rich in C ranging between 41.9–46.2% (compost) and 34.9–42.5% (three-phase olive mill waste-OMW). The highest content in nitrogen was detected in compost (2–2.45%) followed by pruning residue (0.93–0.99%) and OMW (0.03–0.1%). Compost was considered a good source of phosphorus (0.3–0.6%) followed by pruning residue (0.08–0.13%) and OMW (0.01–0.3%). Potassium was also considerable in the organic materials recycled ranging 0.5–1.5% in compost followed by pruning residue (0.5–0.7%) and OMW (0.3–1.1%). Adoption of modified pruning also had important contribution toward sustainable management of olive trees. Sustainable pruning resulted in a well-balanced ratio between vegetative growth and fruiting (balanced, every year, in order to eradicate biennial bearing). Significant fluctuation in olive yields was observed in the first years of the project while yields were gradually stabilised by applying sustainable crop management. In parallel, yield increase without additional inputs, lowers the carbon—environmental footprint of the product regarding several environmental impact categories. Results can be integrated in the national agricultural and environmental policy in Mediterranean countries toward the achievement of a circular economy.

Keywords: carbon sequestration; circular economy; compost; cover crops; pruning

1. Introduction

Olive is one of the most abundant tree crops in the Mediterranean countries [1]. Olive cultivation is adapted to sloping land and poor soils providing ecological, economic, and social benefits to the areas it is realized [2]. Over the 70% of olive trees globally are cultivated in European Union's Mediterranean countries with Greece being the third producer country in the world with an average annual production of 300.000 Mg olive oil, following Spain and Italy [3].

The Food and Agriculture Organization (F.A.O.) predicts that the world's population will reach 9.1 billion people by 2050 [4]. Food production will have to increase by some 70% above today's levels to keep pace with demand [4]. This increase in food production could be achieved by developing more land for agriculture. However, the negative impact of converting natural forests or other wild habitats on climate change and global biodiversity is well documented [5]. Land use changes (e.g., from forestry to cropland) account for some 12% of all the greenhouse gas emissions that lead to global warming [6]. The impacts of climate change are more dramatic in regions with intense competition for natural resources between agriculture and other economic sectors or in ecosystems that are prone to environmental degradation [7]. Today, there are still many farmers who do not use environmentally friendly cultivation methods with effect on climate change [8–10]. In addition, intensification of olive cultivation across the Mediterranean has been encouraged by subsidies from the European Union leading to rapid landscape change [11].

In May and June 2018, the European Commission (EC) published the financial plan and legislative proposal for the common agricultural policy CAP post-2020. According to that, climate-related risks vary for different regions of Europe, with the Mediterranean region considered to be most threatened [12]. Farming management strategies and processes need to be adjusted with the help of available best practices, policies, and tools, including financial instruments. Especially, southern Mediterranean areas are expected to be the most affected by climate change, with reduced crop yields and degraded ecosystems because of increased temperature, greater risk of drought, and declining water availability. Moreover, in Mediterranean environments, most of the olive production is characterized by low external inputs and low percentage of organic matter in soils. Furthermore, a large part of Mediterranean olive production is realized in hilly areas with shallow soils [12,13].

Up to now, only few of the studies dealing with olive cultivation in the Mediterranean area have systematically tested alternative olive cultivation techniques under Mediterranean conditions [12]. So, the objectives of the present study are to propose and evaluate proper agricultural practices in olive orchards for mitigating climate change effects on olive groves and ensuring environmental benefits of sustainable olive groves management especially in semi-arid regions as the Mediterranean basin. Also, based on the proposed practices, the prevention of land abandonment, the reduction of landslide or soil erosion risk, as well as the conservation of ecosystem integrity (landscape quality and soil functionality) can be achieved.

In this study, the selected farming practices (e.g., no-tillage, mulching of pruning residuals, and supply of organic material) had two-fold objectives: a) To ensure enhanced atmospheric carbon dioxide (CO_2) uptake and its storage in biomass and soil as soil organic matter (SOM) increasing thus soil fertility. At the same time, b) to train olive growers to minimize biennial bearing (the phenomenon of one year with high fruit yield followed by a year with minimal yield), increase yields, and decrease producing costs, mainly by a smart approach to pruning including management of residues (e.g., instead of burning the pruned wood), cover crops, and by minimizing tillage. The overall objective is to use CO_2 as a tool for more environmentally and economically viable olive crop. Also, the proposed practices can be used as guidelines to help farmers on Mediterranean regions adapt to climate change and boost ecosystem as well as landscape functions.

2. Materials and Methods

2.1. Study Area and Treatments

The proposed environment-friendly agricultural practices were implemented in three areas in Greece: (a) southwest Peloponnese (Nileas group of farmers), (b) northeastern Crete (Mirabello Union of Agricultural Cooperatives), and (c) northcentral Crete (Peza Union of Agricultural Cooperatives) (Figure 1a). Forty olive groves per area were selected, of which 20 were used as control plots (C: control) and 20 as demonstration plots (T: treatment) where the proposed agricultural practices were applied. Data presented in this study refer to the plots where the environmentally friendly practices were applied. The climate in Peloponnese area is characterized as a wet Mediterranean climate (mean annual precipitation 780 mm) and in the two areas of Crete as a dry Mediterranean climate (mean annual precipitation 483 mm). Olive groves are commonly located in sloping land and have moderate level of intensification in their management system and planting density 150–200 trees Ha^{-1} (Figure 1).

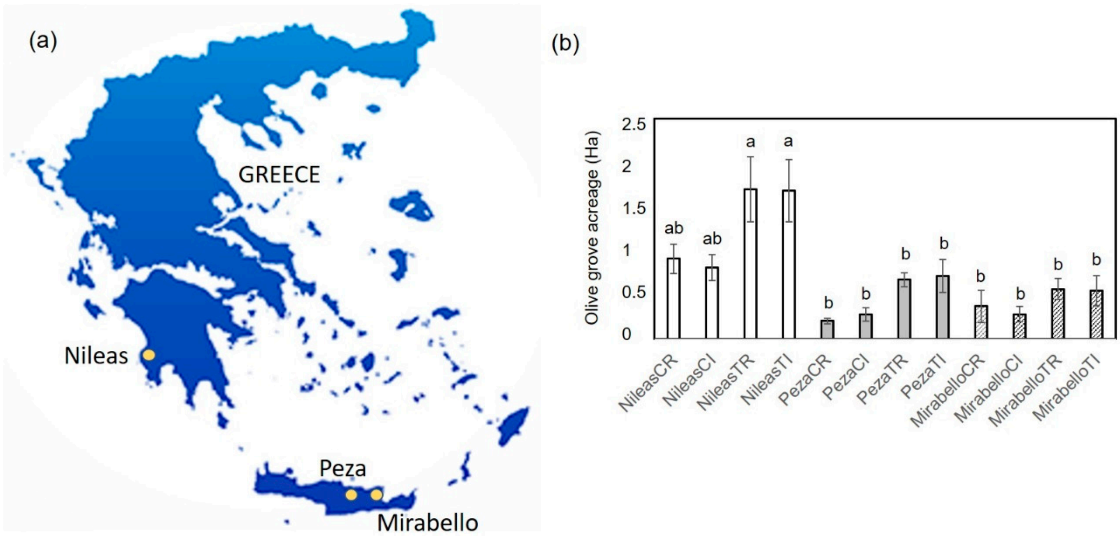

Figure 1. (**a**) The three study areas in Greece (Nileas, Peza, and Mirabello) and (**b**) olive grove acreage (Ha) in each study area. CR: control rainfed, CI: control irrigated, TR: treatment rainfed, TI: treatment irrigated. Bars present means of ten replicates with standard errors. Bars with different letters have statistically significant difference (Tukey test, 0.05).

The proposed set of agricultural practices applied in the T plots included:

1. Pruned wood shredded and spread on the soil surface of the olive groves. Typical practice in all areas was burning pruned wood in bonfires.
2. Small scale composting of organic material (leaves from the local olive oil mills, three-phase olive mill wastewater-OMW, and pruned wood) and spreading on the soil (no incorporation) of the olive groves. Typical practice in all areas was no application of organic materials either composted or raw.
3. Application of a specific pruning pattern and strategy (summer and winter pruning) at an annual basis. Although pruning was applied in all areas, this was focused on facilitation of harvesting and resulted on strong biennial bearing pattern (one year of high yield followed by a year with minimal yield).
4. Enrichment of the natural soil vegetation of the olive groves by cover crops, consisted of a seed combination of 100 kg ha^{-1} leguminous crops (*Vicia sativa, Pisum sativum* subsp. *arvense, Trifolium alexandrinum, Vicia faba* var. *minor,* and *Medicago sativa*) and 10 kg ha^{-1} of seeds of *Avena sativa*, in November or December. Grove vegetation was mowed during spring without being

incorporated into the soil. Typical practice in the area was of no use of cover crops, with soil weed cover during winter, recorded in C plots as less than 40%.

5. Avoidance of soil cultivation and weed control by mowing. Typical practice in the areas was mechanical cultivation with tine harrows or rotavators.

2.2. Laboratory Analyses of Organic Materials

To quantify the contribution of the organic materials used in enhancing carbon, nitrogen, phosphorus, and potassium in olive grove soil, sampling and analyses were applied as described in [14]. In brief, samples were dried at 70 °C to a constant weight and then finely ground with a stainless-steel beater analytical mill. Total N concentration was determined colorimetrically after wet digestion (Kjeldhal method) of a subsample of 0.05 g of dry tissue [15]. Another subsample of 1 g was ashed in a muffle furnace at 550 °C for 6 h and then digested with 5 mL of concentrated HNO_3 69% [16]. The concentration of potassium was determined by ICP-OES and of phosphorus by the vanado-molybdate method [16]. For the present study, 41 samples of pruning residue, 51 samples of 3-phase olive mill waste (OMW), and 88 samples of compost were employed.

2.3. Determination of Olive Yield

Annual olive oil yields (Kg Ha^{-1} $year^{-1}$) were recorded for six years (2011–2016) in all 60 T-plots of the study (20 olive groves in Nileas, 20 in Mirabello and 20 in Peza). This period included two years prior to the onset of sustainable management practice application (2011–2012) as a reference of previous status, and four years (2013–2016) of practice application. During 2013, an early heat wave occurred during May damaging the flowering and resulting in reduced fruit yield mainly in Crete.

2.4. Statistical Analysis

Data were analyzed using the SPSS 19 software (IBM SPSS Inc., Chicago, IL, USA) and were subjected to one-way analysis of variance (ANOVA). Significantly different means between control treated olive groves were statistically analyzed by Tukey or LSD test at $P \leq 0.05$. The number of replicates (n) for each measured parameter is specified in the figure or table captions.

3. Results and Discussion

Olive groves differed significantly in size between Crete and Peloponnese, as shown in Figure 1b. Although not relevant to the total farmer's property size, this figure is indicative of the management problems arising, especially in Crete, where one family may have to manage as many as 20 small-sized olive groves dispersed in their area. Organic material added in T olive groves contributed to the addition of carbon, nitrogen, phosphorus, and potassium to the soil. Indicative content is presented in Figure 2. Carbon content was highest in pruning residue (53.8–54.2%) while all materials studied were considered rich in C ranging between 41.9–46.2% (compost) and 34.9–42.5% (three-phase olive mill waste-OMW). On a dry weight basis, N content was highest in compost (2–2.45%) followed by pruning residue (0.93–0.99%) and OMW (0.03–0.1%) (Figure 2). Similar patterns were observed for P, with compost having a higher content of P (0.3–0.6%), as compared to pruning residue (0.08–0.13%) and OMW (0.01–0.3%) and for K, with compost ranging 0.5–1.5% as compared to 0.5–0.7% for pruning residue and 0.3–1.1% for OMW.

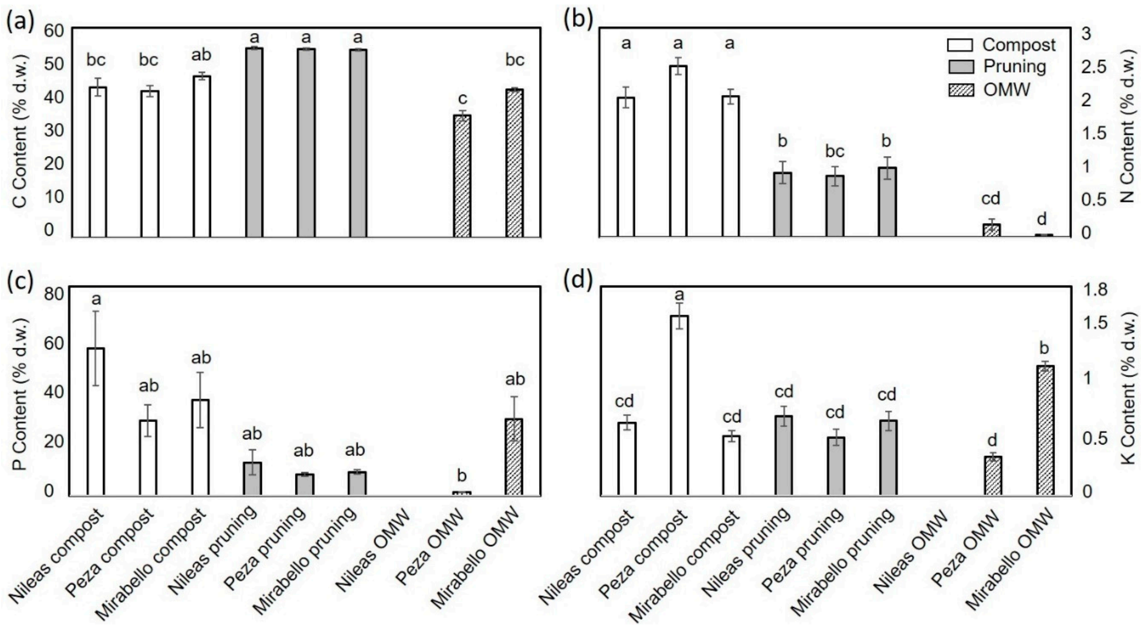

Figure 2. Content of organic materials (compost, pruning residue, three phase olive mill waste—OMW) recycled in olive groves in (**a**) carbon, (**b**) nitrogen, (**c**) phosphorus, and (**d**) potassium in the three study areas in Greece (Nileas, Peza, and Mirabello). Bars present means with standard errors. Bars with different letters have statistically significant difference (Tukey test, 0.05). The number of samples used in the graphs were 180 for C, 179 for N, 177 for P and 167 for K. In Nileas, olive mill waste (OMW) from three-phase mill was not available because all olive mills were two-phased.

If the rate of application (kg Ha^{-1}) of each organic material is taken into account, then compost was by far the highest contributor of C, N, P, and K addition to the soil (Table 1), followed by pruning residue and olive mill waste. As compared to the actual olive tree requirements in N, P, and K, the total addition of these mineral nutrients may only represent less than 50% for N and less than 20% for K and P. However, the effect of organic material on mineral nutrient availability in the soil is quite complicated and not only based on the absolute amounts of nutrients added. This is reflected in previous work published referring to the same demonstration plots, where soil organic matter (+28%), as well as main macro- and micronutrients (N +35%, P +64%, K +44%, Ca +62%, Mg +34%) were markedly improved following three years of increased biomass inputs [14]. Moreover, soil basal microbial respiration increased (+100%) by the addition of organic materials and this effect was more profound at 0–10 cm in comparison to 10–20 cm depth [17]. Higher annual levels of soil moisture (+12%) were observed in sustainably managed olive groves as compared with intensive production system, as well as in the rainy (winter) period (+40%) as compared with the dry summer period [18,19].

Table 1. Annual contribution of recycling organic materials of the olive groves in the budget of carbon (C), nitrogen (N), phosphorus (P), and potassium (K). Calculation was based on the content presented in Figure 2 and the amounts of organic materials applied in 60 olive parcels in three areas during 2012–2014.

Organic Material	**Contribution (kg Ha^{-1} $year^{-1}$)**			
	C	**N**	**P**	**K**
Compost	652.08	44.46	2.5	14.35
Three phase olive mill waste (OWM)	91.28	0.07	0.02	0.9
Pruning residue	240.59	4.37	0.44	3.42

The above-mentioned results contributed to a significant increase in fruit yield (+39%) in T-plots as compared to C-plots [20]. The capacity of superficial soil to store carbon and mineral nutrients under the olive tree canopy was higher compared to the soil between tree rows (SOM +16%, N +19%) [21,22] because the added organic matter was localized around the trees. In addition, the beneficial impact of increased soil carbon in the olive grove conceivably have improved the grove resilience (e.g., reduction of soil erosion and run-off,) via increasing soil structure and function (e.g., macroporosity, soil hydraulic conductivity, soil water holding capacity) [20–22].

The effect of recycling biomass on soil characteristics was affected by climatic conditions and especially by precipitation. The impact of irrigation conditions (irrigated groves as compared to rain-fed) on chemical and microbial parameters was minimal in SW Peloponnese because the area is characterized by high precipitation [11] and this masked any irrigation effect on soil properties. On the other hand, soil properties in the pilot regions of Crete differed between rainfed and irrigated olive groves [21,22]. SOM (+37%), total nitrogen (+34%), soil basal respiration (+6%), and soil microbial biomass C (+11%) and the humic acid/fulvic acid ratio (+48%) significantly increased with irrigation compared to rain-fed conditions, thereby promoting soil fertility. In fact, the effect was more pronounced for SOM and total nitrogen (TN) in irrigated fields receiving organic materials [22]. This finding was attributed to favorable soil moisture conditions, enhancing vegetation biomass and the soil microorganisms' activity.

The main difference between the two major locations, Peloponnese and Crete, is the level of annual precipitation (higher in Peloponnese) and its distribution (more uniform throughout the year in Peloponnese, while condensed mainly in winter in Crete). For this reason, we suggest that cover crops lifetime could be prolonged in Peloponnese up to April in years with sufficient spring rainfall. In contrast, in Crete cover crops should be ended by the end of March, at the latest, to avoid water competition with olive trees. For the same climatic reasons, we encourage farmers in Nileas to perform summer pruning in addition to winter pruning to regulate vegetation and fruit load. In the case of Crete, summer pruning would also be beneficial in irrigated olive groves for reducing excessive vegetation and in rainfed olive groves to adapt trees to years of very low precipitation. Also, the addition of organic materials on the soil surface of olive groves should be implemented during the period autumn-spring in Crete, when mild temperature and sufficient moisture form a favorable context for SOM built-up and prevent its oxidation. In Nileas, organic materials could be added throughout an extended period of the year because of the higher annual precipitation and its more uniform distribution throughout the year.

Another environmental advantage of wood shredding compared to wood burning, is the avoidance of emission of harmful gases generated by the bonfires, such as methanol, acetonitrile, acrolein, benzene, toluene, and xylenes [23]. When shredded wood is spread on the ground or composted, it can reduce the need for industrial fertilizers by the olive grower, as 1000 kg of dry wood can replace 6.5, 9.0, and 3.0 kg Ha^{-1} of N, P, and K respectively, according to the analyses performed on shredded wood by the project LIFE oLIVECLIMA. At the same time, it may add up to 550 kg of C Ha^{-1} to enrich SOM, but the environmental benefit of avoiding the extraction of 300–400 kg of heating fuel (per 1000 kg of dry wood) is still debatable in the context of the PEFCR development, for the fear of possible double counting, as it happens sometimes with biofuels [24,25].

Adoption of modified pruning also had important contribution towards sustainable management of olive trees. Sustainable pruning resulted in a more balanced ratio between vegetative growth and fruiting. This is reflected by the stabilization of mean annual yields in T-plots during the last three years of the project (2014–2016), as shown in Figure 3. During the three years prior to the onset of the treatments (2011–2013), annual yield fluctuation reached 100% while during the three years of modified pruning application (2014–2016), annual yield fluctuation was lower than 10%. Yield is the complicated outcome of the effect of several environmental and orchard management factors. Therefore, in the present study, where treatment represented a certain orchard management approach, which in turn included modification of several agricultural practices, it is not easy to attribute effects on yield to a single factor. However, it is reasonable to assume that modified pruning contributed significantly to the reduction of the biennial bearing fluctuation along with the improved soil water content and nutrient availability already mentioned before. The pruning method proposed by the project focused on two aims: (a) To increase as much as possible the canopy horizontal spread, so as to increase photosynthesis and carbon dioxide assimilation, and (b) to increase yield in kg of fruit Ha^{-1} and olive oil content % of fruit (mostly affected by exposure to sun).

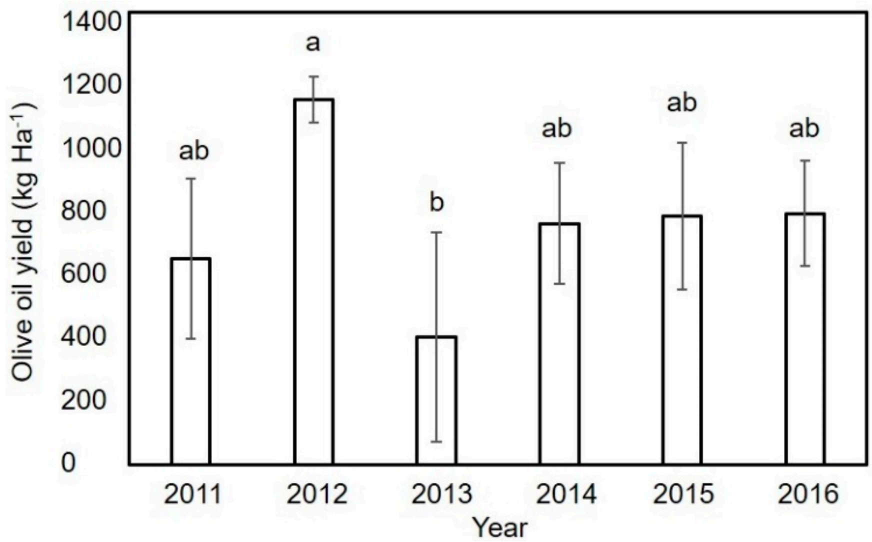

Figure 3. Evolution of olive oil production (Kg Ha^{-1}) per year during 2011–2016 in the three study areas in Greece (Nileas, Peza, and Mirabello). Bars present means of 60 replicates with standard errors. The means of the three study areas were analysed. Bars with different letters have statistically significant difference (LSD test, 0.05).

Wood, in its turn can be separated in the part that will be annually removed by pruning and the wood that will become part of the permanent structure of the trees, i.e., roots and trunk. As it is well established that the trunk of olive trees expands in diameter by age, it is certain that in spite of any carbon losses due to autotrophic respiration, the bottom-line is that a large part of carbon trapped in the wood will be permanently stored in it, justifying for the carbon credits for olive oil. This has been agreed in the PEFCR context, but calculation details remain to be agreed [26].

Among the practices introduced, pruning should be applied first to reshape the trees and set the foundations for higher efficiency of inputs (water, fertilizers, and labor). It has become obvious to olive growers that the proposed pruning can alleviate the year-to-year alternate bearing of olive trees, a situation that exhausts the trees in the "on" years, rendering them susceptible to adverse conditions in the "off" years, with detrimental effect on yields and production cost.

The project LIFE oLIVECLIMA opened some new avenues of work needed to further support the sustainability of olive crop (Table 2). They are summarised below, by reference to the performed interventions, and according to their importance [25]:

- Pruning: It is proposed to the authorities to incorporate into the Common Agricultural Policy (CAP) measures, specialized training of olive growers for pruning in traditional producing areas, with the objective to ensure the sustainability of the crop, deterring land abandonment, for socio-environmental reasons.
- Pruned wood as fuel: An economic study would help olive growers in an area to decide if building a pelleting facility would be a viable enterprise within a circular-economy context. Especially, taking in account the prospective of pruning under the regime of climate change. Another objective of a future study would be to determine how is pruned wood modelled in life cycle analysis (LCA) terms. Could it be also used for carbon credits, i.e., as heating fuel replacement?

- Pruned wood as fertilizer: Under zero tillage, there is a question mark on the rate of wood dissipation, as compared to its incorporation within the soil by topsoil fauna, especially by earthworms. A proper carbon balance must be investigated in LCA terms, in order to compare this option for treating the shredded wood vs. using it as fuel. Carbon storage in the permanent structure of the olive trees: This parameter is utterly important for the carbon credits of olive oil, but very uncertain as well. Research would be needed for a method to provide an estimate of permanent wood mass, with limited uncertainty, in order to be suitable for robust PEF calculations.
- Risk for disease spreading by pruned wood shredding: Care should be given to avoid recycling of pruning residue in cases that trees are infected by *Verticillium dahlia* or other pathogens. It is important to carry out monitoring, if in doubt.

Table 2. Improvement achieved through applying innovative cultivation practices in comparison to the traditional olive grove management (business as usual).

Innovations Introduced by oLIVECLIMA	Traditional Practice	Improvement Achieved
Mulching of pruning residues	Burning of pruning residues in bonfires in the olive groves.	Double benefits were achieved, (*i*) avoiding of direct emissions of CO_2 into the atmosphere due to burning and (*ii*) increased the carbon matrix supplied and related agronomical and environmental benefits
Small-scale composting of organic raw materials derived from olive oil mills (leaves, potentially also oil mill wastewater and pruned wood).	By-products of mill stored in a field next to the olive mill without any use. There was a high nuisance due to the unpleasant odor and risk of soil and water sources pollution due to leakage.	Activation of circular economy and reduction of costs for waste material management
Implementation of annual pruning techniques focused primarily to enhance within-canopy light distribution (photosynthesis oriented) and aeration of the foliage and good development of bearing shoots	Traditional heavy pruning every three years	Reduction of the "on-off year" phenomenon and achievement of stable yearly production with stable labor employment
Cover crops (a seed-mix based on legumes and cereals)	Seasonal (winter) 40% soil coverage by spontaneous vegetation	Increase of soil covering up to 100 %, increase of biodiversity of the flora at the floor of the olive groves lasting for longer time
No-tillage	Mechanical soil tillage with tine harrows or rotavators.	Reduction of soil CO_2 emissions triggered by soil tillage, reduction of economic and environmental costs related to fuel consumption required for traditional practice; promotion of cover crops development

Because of the complex interactions that characterize the cover crop and no-tillage management systems, these are not discussed in the present paper. Detailed information on these systems can be found in [14]. Results of the present study can be integrated in the national agricultural and environmental policy in Mediterranean countries toward the achievement of a circular economy. The green payment scheme of the E.C. provides a framework for such policy incentives for environmentally friendly agriculture. Support payments based on the fulfilment of environmental constraints may contribute to the achievement of environmental outcomes compared to coupled support without restrictions, but, some unforeseen environmental impacts may also be observed [26–28].

4. Conclusions

This field-scale study aimed to relate olive yields to soil parameters and carbon sequestration. Olive cultivation can adapt to changing climatic conditions by applying an orchard management system based on two pillars: (a) Improved soil fertility through soil organic matter raise, and (b) pruning-induced adjustment of tree growth and fruit load to the available water, nutrients and to weather in each area and year. Recycling of locally available organic materials may contribute to increasing carbon storage in the soil and provide mineral nutrients for the trees, although they are, in most cases, not sufficient to substitute industrial fertilizers. Stabilization of yields, reduction of commercial inputs, and enhancing agroecosystem resilience are achievable in Mediterranean olive groves by applying simple farming practices.

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