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LCA-Based Environmental Performance of Olive Cultivation in Northwestern Greece: From Rainfed to Irrigated through Conventional and Smart Crop Management Practices

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Abstract: Olive cultivation is expanding rapidly in the northwestern part of Greece, under both rainfed and irrigated practices. Irrigation can result in larger yields and economic returns, but trade-offs in the water–energy–pollution nexus remain a controversial and challenging issue. This study presents an environmental Life Cycle Assessment (LCA) of Greek olive orchard systems in the plain of Arta (Epirus), comparing rainfed (baseline), Decision Support System (DSS)-based (smart) irrigation practices and farmer experience-based (conventional) irrigation practices. The contributions in this paper are, first, to provide a first quantitative indication of the environmental performance of Greek olive growing systems under different management strategies, and second, to detail the advantages that can be achieved using smart irrigation in olive cultivation in the Greek and Mediterranean contexts. Eighteen midpoints (e.g., climate change, water scarcity, acidification, freshwater eutrophication, etc.), two endpoints (damages on human health and ecosystem quality), and a single score (overall environmental impact) were quantified using the IMPACT World+ life cycle impact assessment method. The LCA model was set up using the OpenLCA software v1.10.3. The functional units were 1 ton of product (mass-based) and 1 ha of cultivated area (area-based) on a cradle-to-farm gate perspective. Irrigated systems had the lowest impacts per mass unit due to higher yields, but showed the highest impacts per cultivated area. The DSS-based irrigation management could reduce water and energy use by 42.1% compared to conventional practices. This is translated into a reduction of 5.3% per 1 ton and 10.4% per 1 ha of the total environmental impact. A sensitivity analysis of impact assessment models demonstrated that the benefits could be up to 18% for 1 ton of product or 22.6% for 1 ha of cultivated land. These results outline that DSS-based irrigation is a promising option to support less resource-intensive and sustainable intensification of irrigated agriculture systems in the plain of Arta.

Keywords: life cycle assessment; olives; agricultural irrigation; decision support systems; smart agriculture; Greece

1. Introduction

The olive (*Olea europaea* L.) is one of the most important perennial Mediterranean crops with overriding importance in terms of employment and contribution to farm income [1]. It possesses multiple significance for Greece in financial, social, and ecological terms [2].

Greece is the world's third-largest producer of olive-based products, after Spain and Italy. It encompasses 1 million hectares of olive groves, corresponding to 17% of the total world production of olive fruit. Regarding table olives, Greece produces annually more than 200,000 tons, which account for 25% and 7% of EU and global production, respectively [3]. The plain of Arta (Region of Epirus, Greece) is one of the most significant areas for table olive production in Greece. Olive groves account for 12% of the total and 22% of the irrigated agricultural land of the plain [4].

Although the olive tree is a well-adapted species to the Mediterranean-type climate, new challenges are predicted to arise from climate change, threatening this traditional crop [5]. In the future, in some Mediterranean areas including Greece, rainfed cultivation could not be economically feasible and wherever water is available, it would be replaced by irrigated olive cultivation [6]. Irrigation is a valuable agricultural practice for table olive cultivation since it affects not only final yields and fruit size but also qualitative characteristics of the olive fruit [7]. However, current changes and future climatic scenarios indicate significant and increasing water demand [8], underlining the specialized guidance needed to rationalize the use of irrigation water use and application rates. Agronomic management practices in developed countries are generally based on farmers' empirical experience, resulting in over-application of irrigation water and nutrients [9]. On the other hand, extra energy is required not only to convey water from the delivery point to the crops [10] but also for the production and transportation of fertilizers [11]. The imbalance of water supply and demand may aggravate water exploitation and depletion, leading to unsustainable exploitation of water resources. Energy consumption for irrigation has major environmental implications due to fossil fuel combustion or higher fossil energy use in electrical grids [12]. Many over-intensified farming systems and false practices contribute to ineffective water use (consumptive and degradative), ammonia volatilization, and greenhouse gas emissions, causing multiple environmental burdens [13].

The increasing use of smart farming is repeatedly described as a panacea that contributes to the sustainability of agricultural production [14]. For this purpose, a variety of sensors and Decision Support Systems (DSS) have been proposed to provide efficient use of natural resources [15,16]. Nonetheless, only a comprehensive integrated assessment along the life cycle stages of a product may ensure a robust analysis of the benefit of the innovation [17]. The Life Cycle Assessment (LCA) has received increasing attention over the years for evidencing and analyzing the environmental impacts along the life cycle of a product. Olive cultivation and olive oil production have been largely studied through LCA, as presented in the review by Espadas-Aldana et al. [18]. Latterly, LCA was applied by Fernandez-Lobato et al. [19] to compare traditional rainfed, traditional irrigated, and intensive Spanish irrigated olives, including the processing phase. Maffia [20] evaluated the environmental impacts of the production of olive oil in the Italian region of Campania by comparing six olive oil production systems (two organic certified, two integrated, and two organic hobbyists). Ben Abdallah et al. [21], using LCA, compared traditional, intensive, and super-intensive systems under conventional or organic practice in the olive growing systems in Tunisia. Yet, across the international literature, very few studies have documented and used LCA directly linking the effect of smart farming to environmental impacts [14]. For instance, Mehmeti et al. [22] conducted an eco-efficiency analysis of a real-time irrigation management tool for more precise on-farm inputs in a large irrigation scheme. Balafoutis et al. [23] analyzed variable rate water and nutrient applications in grape cultivation but focused its LCA only on greenhouse gas (GHG) emissions. Palacios et al. [24] proposed a DSS for the correct fertilization and used LCA to quantify its environmental contribution in sugarcane agriculture. Vatsanidou et al. [25] used LCA to analyze different N fertilizer application systems in a Greek pear orchard. Recently, Bacenetti et al. [26] performed LCA to evaluate variable rate nitrogen fertilization in paddy rice under farmer perceptions of crop needs and a new smart app coupled with satellite data. The need for further LCA studies on smart farming and technologies is evident to further verify benefits using the best available knowledge and practice.

In this paper, we present an environmental LCA of rainfed and irrigated olive systems in the Plain of Arta, northwestern Greece. We analyzed two different irrigation practices: conventional irrigation based on farmer perceptions of crop needs and smart irrigation based on a web-based irrigation decision support system. Our leading research questions are first whether producing olive with irrigation would lead to higher, or lower, impacts than producing under rainfed; and second whether, and to which extent smart irrigation may contribute to the reduction of the environmental impact. The main contribution of our work lies in broadening current limited LCA knowledge on the performance of olive-based systems and products in Greece [27,28]. The results provide quantitative information on the product life cycle performance of Greek olive orchards and scientific support on the environmental benefits of assisted irrigation management in crop cultivation. Additionally, provide a useful state-of-the-art reference on the LCA performance of olive cultivation in the Mediterranean contexts.

2. Materials and Methods

2.1. Study Area

The plain of Arta (Figure 1) is located in the northwestern part of Greece, in the Region of Epirus, and has a total area of about 45,000 ha [5]. The climate of Arta's plain is of Mediterranean type, characterized by hot summers and rainy moderate winters. The climatic annual precipitation is about 1100 mm, concentrated mainly during winter months, rendering irrigation a necessity during summer [29,30]. Two large rivers (Arachthos and Louros) traverse the plain, being its main irrigation water source.

Figure 1. Map of Greece, Epirus region, and plain of Arta (green spot) in northwestern Greece.

The prevailing crops in the plain consist of citrus, olive, and kiwifruit trees, along with some arable crops. Olive is one of the most important crops in terms of surface area at a regional level, with about 5500 ha of cultivated land, of which 30% is irrigated [5]. The area of table olive groves that are registered for Common Agricultural Policy (CAP) subsidies occupy almost 3200 ha [31]. The average planting density is 250 trees per ha. The main inputs during the olive life cycle are energy (electricity and fuel) consumption, water consumption, and the use of chemical products (pesticides and fertilizers). Fertilization is carried out early in the year (January–March) in both rainfed and irrigated groves.

Plant protection is applied from late spring to September aiming at the control of pests such as *Prays oleae* and *Dacus oleae* and diseases such as olive leaf spot (*Spilocaea oleagina*). Weeds are controlled using mechanical (mowing) rather than chemical means. Many olive groves in the area are rainfed, but a significant part is irrigated. The climate-based crop water requirement for olive crops during the irrigation period was estimated using FAO's CropWAT [32] to be almost 500 mm, while the corresponding effective rainfall was about 400 mm. The average gross irrigation volume that was measured in selected conventional groves at a representative area for olive culture at the plain of Arta (Village of Grammenitsa, 39.184° N, 20.981° E) during 2019 and 2020 was 318.5 mm/year while the corresponding average applied quantity, as derived from interviews, was almost 400 mm/year. The climatic data for the study area are given in Table 1.

Table 1. Climate data for the study area.

Month	Prc.	Wet Days.	Tmp. min.	Tmp. max.	Tmp. Mean	Rel. Hum.	Sun-shine	Wind (2 m)	ETo
	mm/m	days	°C	°C	°C	%	%	m/s	mm/d
Jan	131	12.7	3.5	11.9	7.7	73.2	48.4	1	0.9
Feb	130	12.2	4.1	13.1	8.6	71.8	49.7	1.1	1.3
Mar	92	11.1	5.9	15.8	10.8	69.3	53.4	1	2
Apr	74	10.9	8.7	19.4	14	68.3	57.5	1	2.9
May	50	8.8	12.6	24.1	18.3	65	66.1	0.9	3.9
Jun	24	5.3	15.6	28.2	21.9	60.2	76.7	0.8	4.9
Jul	14	3.5	18	31.1	24.5	56.9	86.8	0.8	5.4
Aug	18	3.5	18.1	31.1	24.6	57.7	84.4	0.8	4.9
Sep	44	5	15.6	28.3	21.9	62.9	75.8	0.8	3.6
Oct	115	9.6	11.8	21.7	16.7	68.6	62.4	0.8	2.1
Nov	169	12.6	8	17.2	12.6	75.4	51.2	0.7	1.1
Dec	179	13.9	4.9	13.1	9	75.8	44.8	0.9	0.8

Irrigation is performed using micro-sprinklers operating at a pressure of 1.0–2.0 bars. Surface water (SW) and, in some cases, groundwater (GW) are mainly used as irrigation water sources. The share of SW/GW is 95%/5%. Electricity is the main power source for pump operation (90% of farms), while diesel is also used. The average pumping depth is 35–40 m. The soil in the area is characterized according to the USDA classification as clay loam.

2.2. Methodology

Figure 2 shows the methodology steps adopted to evaluate the potential environmental impacts. LCA is based on four main phases: (1) goal and scope, (2) inventory analysis, (3) impact assessment, and (4) interpretation. The first phase defines the start with goal and scope statement defining functional unit and system boundaries, intended application, and audience. Agricultural life cycle inventory data were collected using the data collection template of the Agricultural Life Cycle Inventory Generator [33] and modeled following AusAgLCI [34] and WFLDB guidelines [35]. For impact assessment, a consistent midpoint-damage framework was used [36]. The methodology is explained in detail in the following sections.

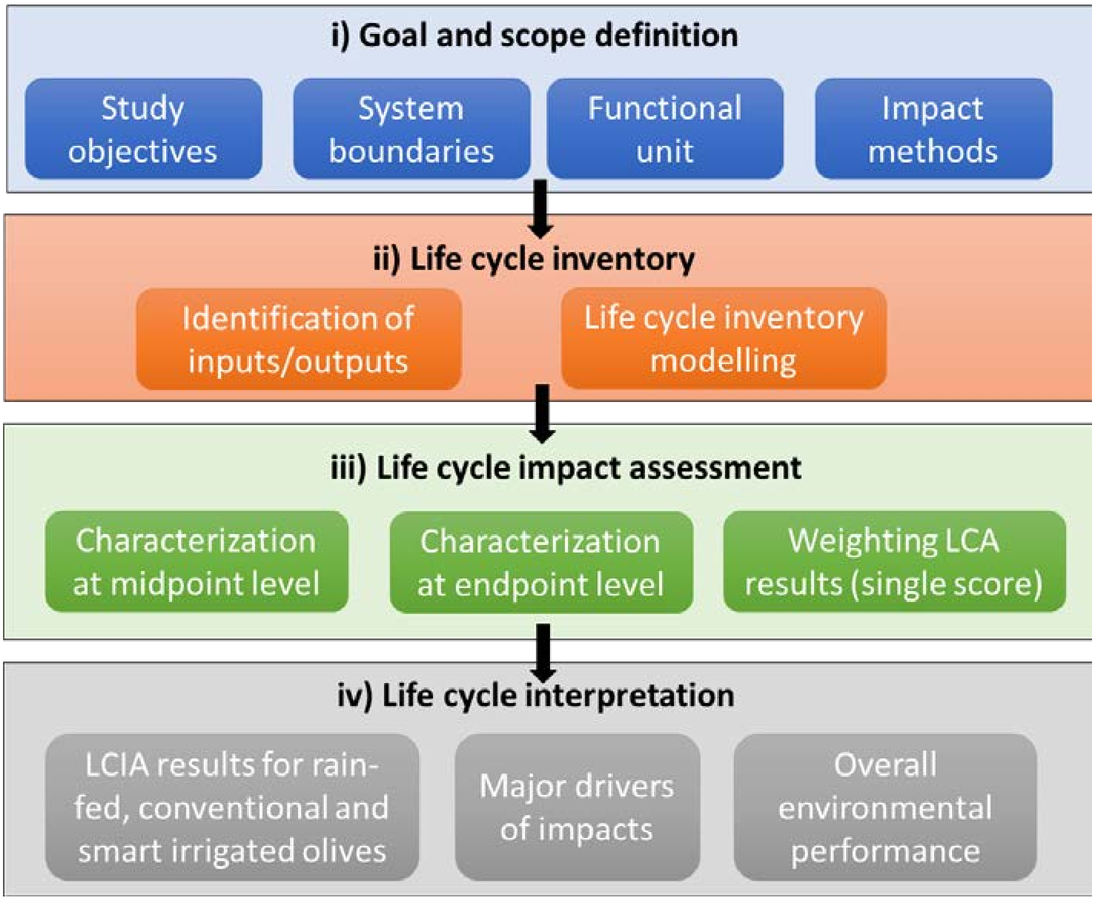

Figure 2. Diagram of the LCA framework used in this study.

2.2.1. Goal and Scope Definition

The goal of this study was the LCA-based impact assessment of rainfed and irrigated olive orchards. The rainfed cropping system was utilized as a baseline scenario. Two irrigation strategies were compared. In the conventional scenario, the irrigation water was supplied based on farmer experience based on the perception of soil water status and crop reactions. For the smart scenario, the performance of IRMA_SYS DSS [37] was analyzed. IRMA_SYS DSS combines actual agrometeorological data along with crop parameters and has provided crop-specific recommendations for irrigation in the whole plain of Arta since 2015. The target group of this study includes local stakeholders (farmers, irrigation managers, and local government officials) and agriculture-related LCA practitioners. The scope of this study was defined as a cradle-to-farm gate (Figure 3). The following activities were included in the analysis: raw materials extraction (e.g., fossil fuels), manufacture of the agricultural inputs (fertilizers, pesticides, electricity, diesel, etc.), use of the agricultural inputs (water emissions, fertilizers emissions, diesel fuel emissions, and pesticide emission), and maintenance and final disposal of machines. Irrigation, tractors, fertilizers, and pesticides were combined to produce the overall product system footprint. Two functional units (FU) were defined: 1 ton (mass-based) of the freshly harvested olives at the farm exit gate and 1 ha of cultivated land (area-based). In this way, both eco-efficiency of production and farm impact intensity and under irrigation and rainfed conditions are addressed [38].

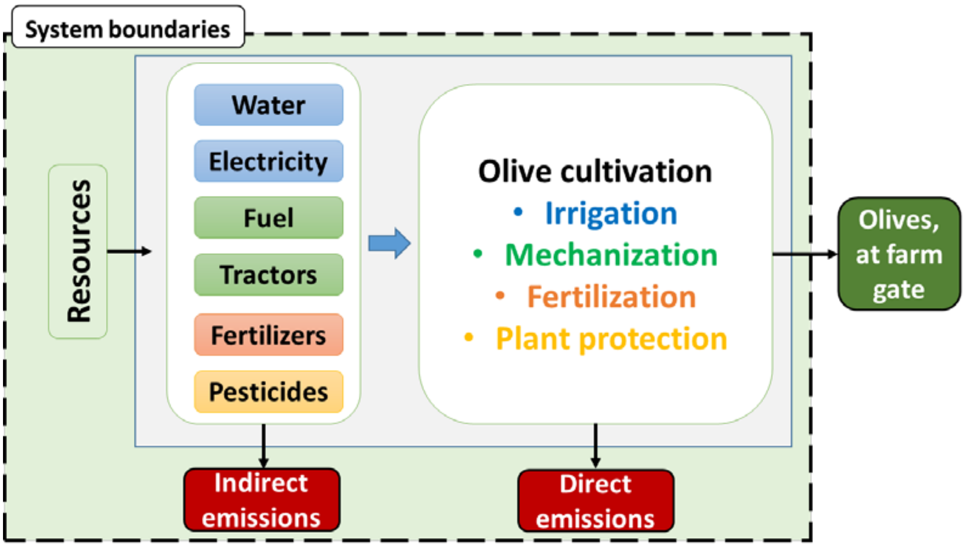

Figure 3. System boundary for LCA of olive production systems.

2.2.2. Life Cycle Inventory

Table 2 reports the main inventory data about the cultivated crops. The Life Cycle Inventory (LCI) in this LCA is a mixture of measured, collected from the questionnaire surveys, and calculated data. This study refers to two cultivation cycles, 2019 and 2020. These data were collected from producers involved in this study. The orchard density was 240 trees per hectare. The lifespan of the orchard was considered 25 years. Secondary data were retrieved from databases, literature, or estimated using specific models. N-related emissions were estimated, based on the registered use of fertilizers and using specific models and IPCC guidelines (2006). Ammonia (NH_3) accounted for 10% of the applied N. Direct N_2O emissions were calculated as 1% (0.01 kgN_2O-N/kgN) and 2.1% (0.021 kgN_2O-N/kgN) of the applied N for rainfed and irrigated crops, respectively. Nitrogen oxides (NO_x) emissions to air were calculated as 21% of the direct N_2O [39]. The fraction of N synthetic fertilizers that volatilizes as NH_3 and NOx (FracN$_{GASF}$) was 10% (kg N volatilized/kg of the applied N). The fraction of N lost through leaching and runoff (FracNLEACH) was assumed 0.3 (kg N/kg N additions). Phosphorus emissions included phosphorus leaching to groundwater, run-off to surface waters, and emissions through erosion by water to surface waters. These emissions were modeled according to available guidelines [34,39]. Diesel combustion and pesticide emissions were sourced from Ecoinvent Database 3.1 (2014). Indirect inventory data (emission profile) for the production of inputs were retrieved from Ecoinvent v.3.1 database [40].

Table 2. Inventory data for LCA performance of olive growing systems in the plain of Arta.

Parameter.	Unit	Average Rainfed [min;max]	Average Farmer-Led Irrigation [min;max]	Average DSS Based Irrigation [min;max]
Crop yield	ton/ha	5.66 [3.4;7.9]	11.84 [7;16.6]	11.23 [6.6;15.8]
Irrigation water	m^3/ha	-	3560 [2962.5;4155]	1953 [1885;2020.4]
Electricity for irrigation (Greek mix)	kWh/ha	-	687 [802;571.7]	377 [363.5;389]
Nitrogen fertilizer, as N	kg/ha	135 [96;172.8]	135 [96;172.8]	135 [96;172.8]
Phosphorus fertilizer, as P_2O_5	kg/ha	84 [48;120]	84 [48;120]	84 [48;120]
Potassium fertilizer, as K_2O	kg/ha	60 [54;60]	60 [54;60]	60 [54;60]
Pesticides, unspecified	kg/ha	21.6	21.6	21.6
Diesel	MJ/ha	3913	3913	3913
Tractor, 4-wheel, agricultural	kg/ha	10.56	10.56	10.56
Tractor lubricating oil	kg/ha	2.1	2.1	2.1
Land Occupation, permanent crop	$m^2 * a$	44.16	21.1	22.3

2.2.3. Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) was performed using IMPACT World+ (IW+), a novel method [36] combining characterization, normalization, damage assessment, and weighting (Table 3). We firstly computed 18 midpoint impacts (climate change, human and eco-toxicity, particulate matter acidification, and eutrophication, but also impacts due to the use of water, land, and resources). Then, the endpoints (damage to human health and ecosystem quality) and a single score assessment assisted the analysis. Endpoint and single score condensed the complexity of the multiple impact indicators, recognized the interdependency of indicators, and allowed easier communication of results to non-LCA experts. The OpenLCA software v.1.10.3 [41] was used to conduct LCIA.

Table 3. IMPACT World+ midpoint-damage impact categories and normalization/weighting factors.

Category	Abbreviation	Damage to Human Health	Damage to Ecosystems
Climate change, long term	CC_lt	+	+
Climate change, short term	CC_st	+	+
Fossil and nuclear energy use	FEU		
Freshwater acidification	FA		+
Freshwater ecotoxicity	FET		+
Freshwater eutrophication	FE		+
Human toxicity cancer	HTc	+	
Human toxicity non-cancer	HTnc	+	
Ionizing radiations	IR	+	
Land occupation, biodiversity	LO		+
Land transformation, biodiversity	LT		+
Marine eutrophication	ME		+
Mineral resources use	MRU		
Ozone layer depletion	OD		
Particulate matter formation	PM	+	
Photochemical oxidant formation	POF	+	
Terrestrial acidification	TA		+
Water scarcity	WS	+	+
Normalization factor	-	13.7	0.000101
Weighting factor	-	5401.460	1386.139

A Monte Carlo uncertainty analysis (1000 runs) with sampling from a lognormal distribution was conducted to determine the influence of data quality on the significance of the study results. Uncertainty scores were assigned to input-output data based on the criteria presented in the Ecoinvent Pedigree matrix (Table A1, Appendix A). Moreover, a sensitivity analysis was performed to determine if different impact assessment methods may lead to different conclusions. The ReCiPe 2016 [42] and Environmental Footprint [43] model results were used for sensitivity analysis.

3. Results

3.1. Comparative Results at the Midpoint Level

The results of impact category indicators at the midpoint level for the FU of 1 ton of olives are presented in Table 4. The results show that large increases in yield as a result of irrigation offset the footprint increases in most of the impact categories, except for water scarcity, which is due to the use of blue water (irrigation water). Crop yields and blue water use under irrigated treatments were greater than those of the rainfed system. This is because rainfed cropping has a zero on-farm blue water footprint with no water extracted for irrigation [44]. Similar ranges for the majority of life cycle environmental impacts (the change is less than 10%) were found for both conventional and smart irrigation. Smart irrigation via DSS resulted in better environmental performance compared to conventional for water scarcity (−27%), fossil and nuclear energy use (−13%), and human toxicity (−8%) due to associated water and energy savings. For several other impact categories, the conventional system resulted in a lower footprint than the DSS-based one. This variation in the environmental impacts of irrigation per unit of crop production between conventional and smart irrigation mostly results from differences in crop yield. It is well known that the impacts of irrigated versus rainfed crops depend on the functional unit [21,44–46]. Per 1 ha, in comparison with rainfed, the irrigated olives showed the highest environmental impacts in all categories as they require greater use of inputs of water and energy (Table A2, Appendix A). This finding is consistent with previous relevant findings [21,47]. Obviously, for 1 ha, smart irrigation has less impact than conventional irrigation due to a lower input intensity. Our findings reinforce the importance of the examination of multiple functional units to provide a better understanding of the benefits and trade-offs of practices on the environmental impacts.

Table 4. LCA-based metrics of 1 ton of olive cultivation in the plain of Arta under different management strategies (graded color scale: green = lowest impact, orange = midpoint, red = highest impact).

Impact Categories	Unit/ton	Rainfed (Reference)	Farmer-Led Irrigation (Conventional)	DSS Based Irrigation (Smart)
Climate change, long term	kg CO_2 eq (long)	574.6	400.9	394.5
Climate change, short term	kg CO_2 eq (short)	588.6	409.7	402.9
Fossil and nuclear energy	MJ deprived	2632.6	2045.4	1783.6
Freshwater acidification	kg SO_2 eq	6.80×10^{-6}	4.13×10^{-6}	3.95×10^{-6}
Freshwater ecotoxicity	CTUe	29,236.1	14,744.78	15,193.4
Freshwater eutrophication	kg PO_4 P-lim eq	5.31×10^{-2}	2.56×10^{-2}	2.69×10^{-2}
Human toxicity, cancer	CTUh	4.64×10^{-7}	3.04×10^{-7}	2.82×10^{-7}
Human toxicity, non-cancer	CTUh	2.52×10^{-5}	1.66×10^{-5}	1.53×10^{-5}
Ionizing radiations	Bq C-14 eq	3237.54	1919.20	1848.3
Land occupation, biodiversity	m^2 arable land eq. yr	46.3	22.25	23.43
Land transformation, biodiversity	m^2 arable land eq	0.22	0.11	0.114
Marine eutrophication	kg N N-lim eq	0.258	0.127	0.132
Mineral resources use	kg deprived	3.2	1.59	1.65
Ozone layer depletion	kg CFC-11 eq	1.14×10^{-4}	5.98×10^{-5}	6.05×10^{-5}
Particulate matter formation	kg PM2.5 eq	0.323	0.155	0.163
Photochemical oxidant formation	kg NMVOC eq	2.01	1.112	1.121
Terrestrial acidification	kg SO_2 eq	1.64×10^{-2}	8.55×10^{-3}	8.70×10^{-3}
Water scarcity	m^3 world eq	9084.66	26,131.18	17,196.30

We attempted to compare midpoint results across studies since midpoint modeling is widespread across studies. Nevertheless, the values of each study cannot be directly compared because they are estimated using different LCIA methods. However, it was a useful step to establish basic benchmarking information. Pergola et al. [47] estimated global warming potential referring to 1 ton of olives in Italy to be 110 and 80 kg CO_2 eq for rainfed and irrigated systems, respectively. The eutrophication potential was 0.0595 and 0.0494 kg $PO_4{}^3$ eq while acidification potential 0.43 and 0.63 kg SO_2 eq, respectively. Romero-Gámez et al. [48], comparing olive growing practices in Spain, found that the climate change of rainfed and irrigated conventional olives per 1 ton of product was 277 kg CO_2 eq and 260 kg CO_2 eq, respectively. The eutrophication potential was 0.052 and 0.0548 kg P eq while acidification was 3.27 and 2.88 molc H^+ eq per ton of product. Ben Abdallah et al. [21], comparing rainfed and irrigated conventional olives in Tunisia, found the following impacts per 1 ton of product: climate change, 630.9 and 420.8 kg CO_2 eq; eutrophication, 0.09 and 0.128 kg P eq; acidification, 4.35 and 6.72 molc H^+ equation. Fernández-Lobato et al. [19] found that for 1 ton of olive oil, climate change was 239 kg CO_2 eq, ozone depletion 1.78×10^{-4} kg CFC-11 eq, particulate matter 1.65 kg PM2.5 eq, freshwater eutrophication 0.574 kg P eq, and water resource depletion 52.9 m^3 water eq. The impact varies widely across the reviewed literature and agricultural systems. Russo et al. [27] compared the environmental performance of different olive farming systems in a European context and found that the environmental performances of the olive cultivation in Greece were the best for 14 out of 16 impact categories.

Figure 4 shows the process contribution analysis. At the midpoint level, our findings largely confirm those of other relevant olive-based LCA studies [21,48] in terms of the identification of the main impacts and hotspots. Fertilization and irrigation were the agricultural practices that implied the major contribution in most of the categories considered. In the case of farmer-led practices, the irrigation impacts ranged from 0.018% (land occupation) to 83.3% (water use). In the case of the smart scenario, the irrigation impacts ranged from 0.01% (land occupation) to 73.3% (water use). It was observed that energy consumption in irrigation had a higher contribution to fossil and nuclear energy, ionizing radiation, and human toxicity impacts. Irrigation water use for cultivation had the highest contribution to blue water consumption and therefore to water scarcity. The field emissions such as ammonia and dinitrogen monoxide had the highest contribution to impact categories of particulate matter formation acidification, marine eutrophication, and climate change. Pesticide emissions lea to toxicity impacts and ozone layer depletion.

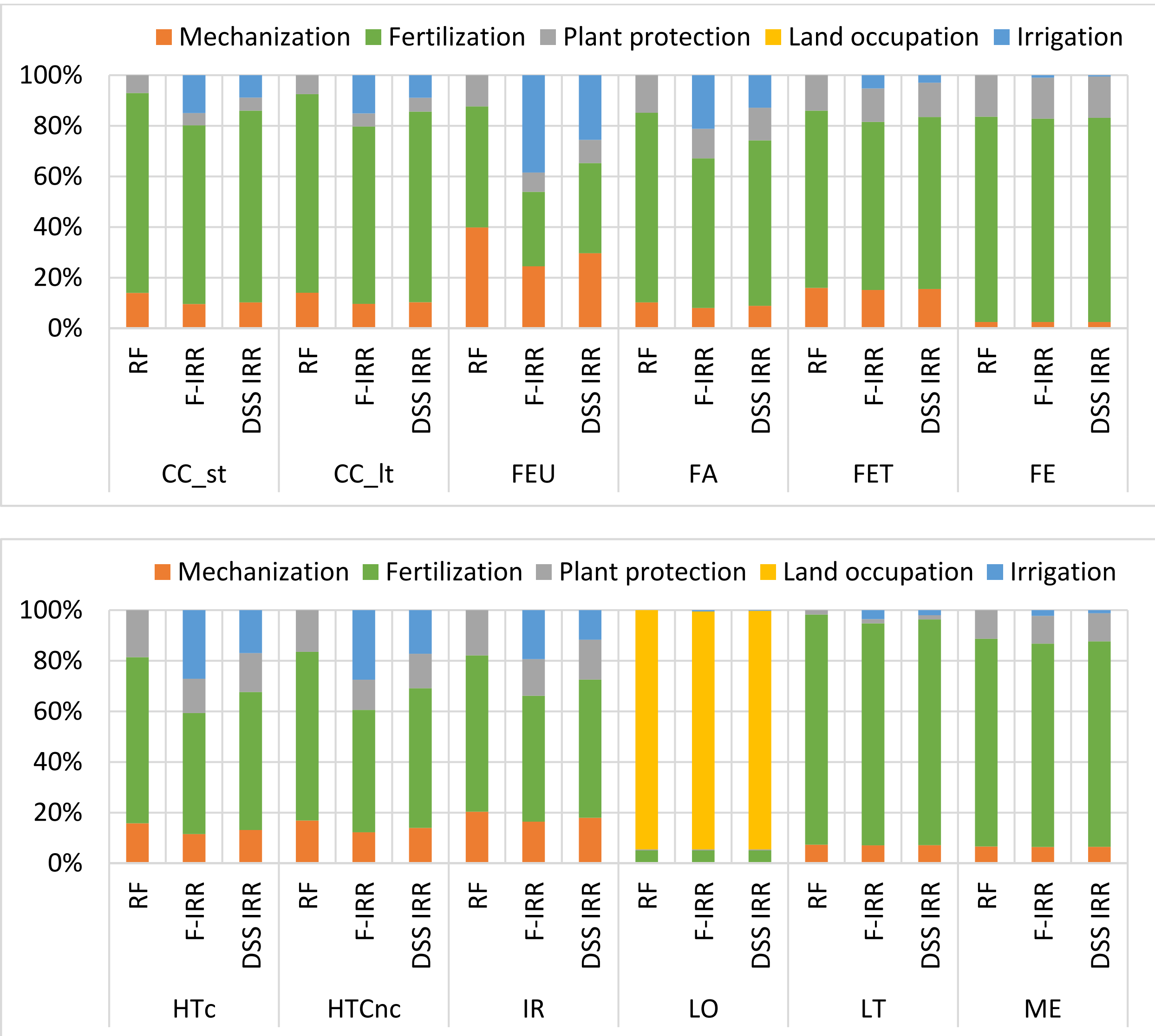

Figure 4. *Cont.*

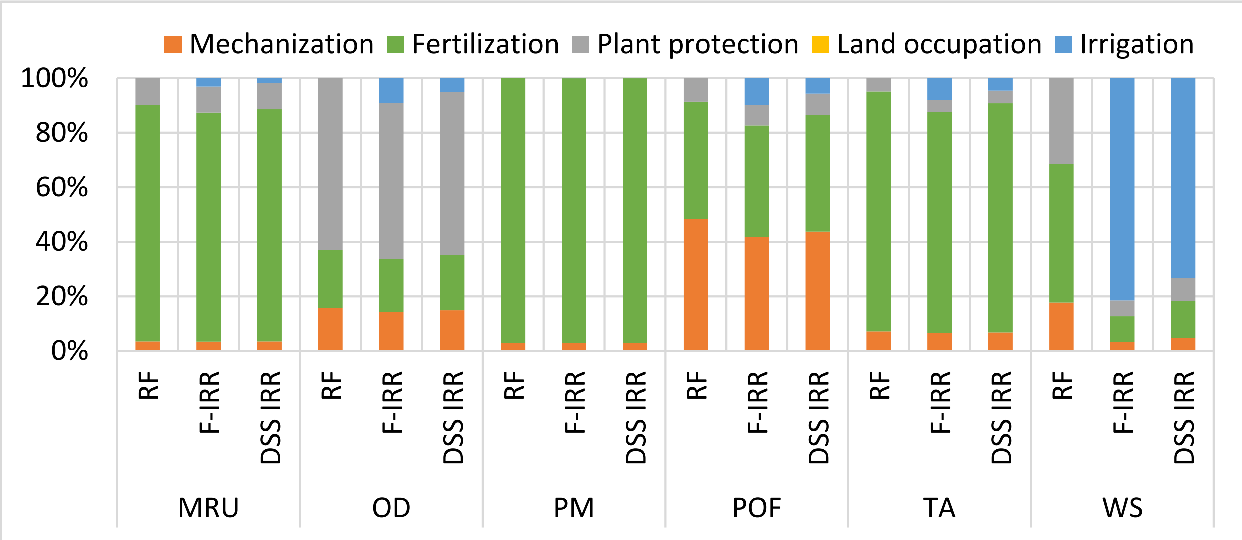

Figure 4. Process contribution analysis on impact categories for rainfed, RF; farmer-led irrigation, F-IRR; DSS-based irrigation, DSS-IRR. Note: CC = climate change; FEU = fossil energy and nuclear use; FA = freshwater acidification; FET = freshwater ecotoxicity; FE = freshwater eutrophication; HTc = human toxicity cancer; HTnc = human toxicity non cancer; IR = ionizing radiation; LO = land occupation; LT = land transformation; ME = marine eutrophication; MRU = mineral resource use; OD = ozone depletion; PM = particulate matter; POF = photochemical ozone formation; TA = terrestrial acidification; WS = water scarcity.

3.2. Endpoint and Overall Environmental Impact

The interpretation of LCA results was extended to the endpoint and single score analysis (Figure 5) to provide an additional basis for a better understanding of the trade-offs between cultivation systems and environmental impacts. It should be reiterated that the higher the score, the more the environmental impact of a crop. Considering impact for 1 ton, it is clear that the irrigated cropping system is more eco-compatible than the rainfed system thanks to its higher olive productivity. The level of damage to human health ranged from 0.0013 DALY/ton for DSS irrigation to 0.0021 DALY/ton for rainfed. The level of damage to ecosystem quality ranged from 361.9 PDF·m^2·yr/ton for DSS irrigation to 520.6 PDF·m^2·yr/ton for rainfed. The final impact as a single score for 1 ton of olives at farm gate were 228.3, 158.4, and 149.9 Euro2003 for the rainfed, farmer-led, and DSS-based irrigation, respectively.

The final results demonstrate that smart irrigation via DSSs produced the lowest environmental impact in terms of damage to human health, ecosystem quality, and overall environmental impact. When the focus is only on irrigation process impacts, the implementation of DSS-based technology benefits translated to 42.2% less damage to human health and 37.5% less damage to ecosystem quality. The final impact could be reduced by 15.2 Euro2003/ton or 40.01%. Overall, however, the DSS-based irrigation management could reduce the product life cycle impacts by 5.3% (1 ton) and 10.4% (1 ha) in comparison with farmer-led irrigation practices. The benefits were limited due to yield and water input trade-offs of DSS versus farmer-led irrigation practices. This was affected also by fertilizers which were identified as the highest contributor to life cycle impact (Figure 5). These results suggest that optimization of fertilization should be the major target to improve LCA results for olive cultivation. This is particularly relevant for rainfed cropping systems. Looking at the impact for 1 ha of olive production (Table A3, Appendix A), the rainfed system had the lowest environmental impact. Based on the weighted results, climate change, particulate matter formation, acidification, and water scarcity were the contributing impact categories.

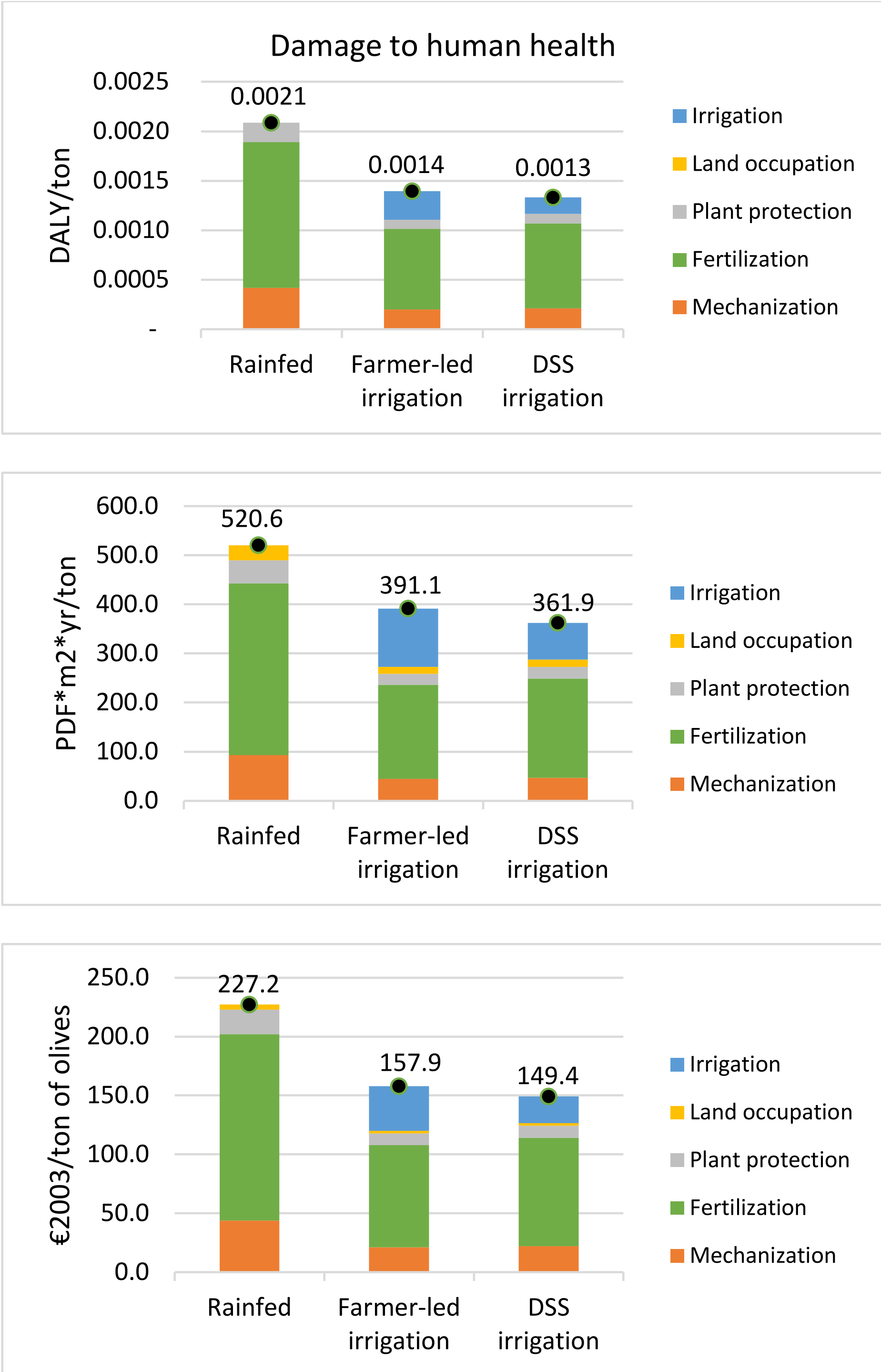

Figure 5. The human health, ecosystem, and overall environmental impact scores of olive cultivation under different management strategies.

The Monte Carlo analysis (Figure 6) revealed that the uncertainty was relatively low for most impact categories with a 10–20% fluctuation range (See Table A4 for numerical results). The uncertainty analysis indicates that the environmental impacts could be around 18% lower for photochemical oxidation formation and 20% higher for particulate matter formation.

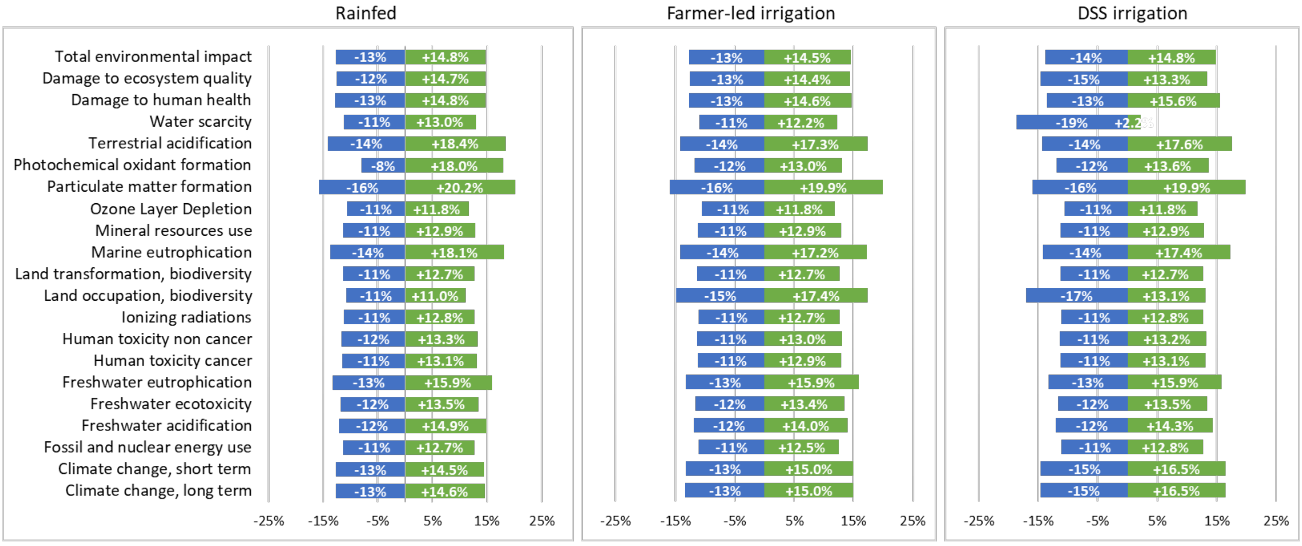

Figure 6. Monte Carlo uncertainty analysis of olive cropping system representing uncertainty per impact category using the IW+ method.

3.3. *Sensitivity Analysis of Life Cycle Assessment Method*

Besides the Impact World+ method, the potential environmental impacts were further computed with ReCiPe 2016 [42] and Environmental Footprint [43] to validate the credibility of the above results. The results as a single score are shown in Figure 7 (See Tables A5 and A6 for detailed LCIA results). At the midpoint level, a similar trend to the IW+ method was found, confirming that irrigated crops have a lower footprint per 1 ton and higher per 1 ha. As expected, substance contributions in each LCIA method were different. Nevertheless, the overall findings from the primary analysis and the sensitivity analysis both confirm that DSS irrigation is the strategy with the lowest environmental impact. The overall benefits of DSS-based irrigation vs. farmer-led irrigation for 1 ton of product were different among methods: 5.3% (IW+), 10.7% (ReCiPe 2016), and 18.1% (EF method). Considering yield data, these benefits for 1 ha become 10.4% (ImpactWorld+), 17% (ReCiPe 2016), and 22.6% (EF method). In all methods, the results showed that the fertilizers remain a great source of impact. The EF method provides a higher benefit since it attributes higher weights to the water use impact category and thereby to irrigation. ReCiPe 2016 confirms fertilizers as the main contributor, with particulate matter, global warming, and human toxicity as the main contributors.

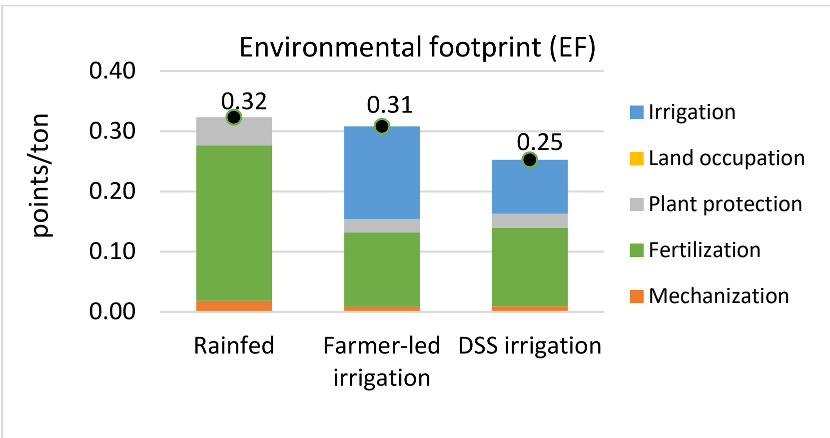

Figure 7. *Cont.*

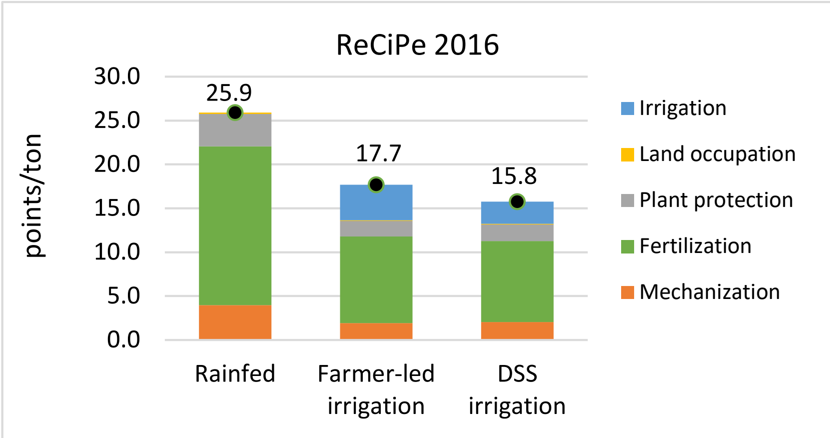

Figure 7. Process contribution to the overall environmental impact of olive cultivation as single score (points) using EF 3.0 (adapted) and ReCiPe 2016 life cycle assessment methods.

4. Conclusions

This is one of the few LCA studies performed so far for table olive growing systems in Greece. Along with the numerical reference for Greek olives, it provided a better understanding of the benefits of using DSSs for irrigation management. The results were studied for two functional units, a mass-based (reflecting production efficiency) and a surface-based unit (reflecting production intensity). The large increases in yield resulting from irrigation offset the increases in footprint due to increased resource inputs compared to the rainfed system. This confirmed that high-yield farming reduces the global environmental impact compared to low-yield olive farming systems. On the other hand, irrigated orchards are likely to increase impacts per unit area of farmland. The use of DSS-based irrigation compared to conventional farmer practices allowed achieving a considerable decrease in water and electricity use of about 42.1%. This reduced the total environmental impacts of the irrigated process by 40% per unit of product and 43% per unit area. However, environmental benefits were drastically reduced when considering all agricultural activities. This is because fertilization was the highest contributor to environmental impacts. Overall, this assessment showed that the total environmental impact could be reduced by 5.3% per 1 ton and 10.4% per 1 ha by changing from conventional to smart irrigation practices. A sensitivity analysis of the LCA method demonstrated that benefits could be higher. This highlights that promising environmental benefits could be achieved using DSS-based irrigation, which can reduce impact intensity and increase efficiency due to more efficient use of inputs. To further enhance the life cycle environmental benefits, the focus should be placed on the development of DSSs optimizing both irrigation and nutrient management. Further studies will be conducted to analyze the sustainability aspect of smart technologies considering cross-cutting economic, environmental, and social effects.

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

Appendix A

Table A1. Data Quality Indicators (DQI) assigned to each input-output flow for uncertainty analysis.

Parameter	DQI	Geometric Standard Deviation
Electricity	2;1;1;1;2	1.0714
N-fertilizer	2;1;1;1;2	1.0714
P-fertilizer	2;1;1;1;2	1.0714
K-fertilizer	2;1;1;1;2	1.0714
Pesticides	2;1;1;1;2	1.0714
Diesel	2;1;1;1;2	1.0714
Tractors	2;1;1;1;2	1.0714
Tractor oil	3;1;1;1;2	1.0714
Land occupation	3;1;1;1;2	1.1155
Ammonia	3;2;1;2;2	1.1155
Dinitrogen monoxide	3;2;1;2;2	1.1155
Nitrous oxide	3;2;1;2;2	1.1155
Nitrates	3;2;1;2;2	1.1155
Phosphorus	3;2;1;2;2	1.1155
Phosphates	3;2;1;2;2	1.1155
Pesticide emissions	3;2;1;2;2	1.1155
Combustion emissions *	3;2;1;2;2	1.1155

* Note: See Table 7.1 page 62 at Necemek and Kagi (2007).

Table A2. LCA-based metrics of 1 ha of olive cultivation in the plain of Arta under different management strategies (graded color scale: green = lowest impact, orange = midpoint, red = highest impact).

Impact Categories	Unit	Rainfed	Farmer Irrigation	DSS Irrigation
Climate change, long term	kg CO_2 eq (long)	3252.2	4747.09	4426.15
Climate change, short term	kg CO_2 eq (short)	3331.5	4851.33	4520.30
Fossil and nuclear energy	MJ deprived	14,900.5	24,217.75	20,011.88
Freshwater acidification	kg SO_2 eq	3.85×10^{-5}	4.89×10^{-5}	4.43×10^{-5}
Freshwater ecotoxicity	CTUe	165,476.5	174,578.17	170,469.62
Freshwater eutrophication	kg PO_4 P-lim eq	0.301	0.304	0.302
Human toxicity, cancer	CTUh	2.62×10^{-6}	3.60×10^{-6}	3.16×10^{-6}
Human toxicity, non-cancer	CTUh	1.42×10^{-4}	1.96×10^{-4}	1.72×10^{-4}
Ionizing radiations	Bq C-14 eq	18,324.502	22,723.270	20,737.646
Land occupation, biodiversity	m^2 arable land eq .yr	262.2	263.4	262.9
Land transformation, biodiversity	m^2 arable land eq	1.26	1.31	1.28
Marine eutrophication	kg N N-lim eq	1.46	1.50	1.49
Mineral resources use	kg deprived	18.21	18.79	18.53
Ozone layer depletion	kg CFC-11 eq	6.44×10^{-4}	7.08×10^{-4}	6.79×10^{-4}
Particulate matter formation	kg PM2.5 eq	1.83	1.83	1.83
Photochemical oxidant formation	kg NMVOC eq	11.38	13.17	12.58
Terrestrial acidification	kg SO_2 eq	0.093	0.101	0.098
Water scarcity	m^3 world eq	51,419.16	277,937.89	19,2942.53

Table A3. Endpoint and single scores indicators of 1 ha of olive cultivation in the plain of Arta under different management strategies.

Impact Categories	Unit	Rainfed	Farmer Irrigation	DSS Irrigation
Damage to human health per 1 ton				
Mechanization	DALY	4.18×10^{-4}	2.00×10^{-4}	2.11×10^{-4}
Fertilizers	DALY	1.47×10^{-3}	8.13×10^{-4}	8.58×10^{-4}
Pesticides	DALY	1.93×10^{-4}	9.24×10^{-5}	9.75×10^{-5}
Land occupation	DALY	-	-	-
Irrigation	DALY	0.00	2.89×10^{-4}	1.67×10^{-4}
Damage to human health per 1 ha				
Mechanization	DALY	2.37×10^{-3}	2.37×10^{-3}	2.37×10^{-3}
Fertilizers	DALY	8.35×10^{-3}	9.63×10^{-3}	9.63×10^{-3}
Pesticides	DALY	1.09×10^{-3}	1.09×10^{-3}	1.09×10^{-3}
Land occupation	DALY	-	-	-
Irrigation	DALY	0.00	3.42×10^{-3}	1.88×10^{-3}
Damage to ecosystem per 1 ton				
Mechanization	PDF·m^2·yr	93.2	44.6	47.0
Fertilizers	PDF·m^2·yr	349.9	191.3	201.9
Pesticides	PDF·m^2·yr	46.7	22.3	23.6
Land occupation	PDF·m^2·yr	30.7	14.7	15.5
Irrigation	PDF·m^2·yr	-	118.2	73.9
Damage to ecosystem per 1 ha				
Mechanization	PDF·m^2·yr	527.7	527.7	527.7
Fertilizers	PDF·m^2·yr	1980.7	2265.1	2265.1
Pesticides	PDF·m^2·yr	264.5	264.5	264.5
Land occupation	PDF·m^2·yr	173.7	173.7	173.7
Irrigation	PDF·m^2·yr	-	1399.7	829.5
Total environmental impact per 1 ton				
Mechanization	EURO2003	44.0	21.03	22.19
Fertilizers	EURO2003	158.1	86.96	91.76
Pesticides	EURO2003	20.9	9.97	10.52
Land occupation	EURO2003	4.3	2.05	2.17
Irrigation	EURO2003	-	37.92	22.72
Total environmental impact per 1 ha				
Mechanization	EURO2003	248.9	248.9	248.9
Fertilizers	EURO2003	894.8	1029.6	1029.6
Pesticides	EURO2003	118.0	118.0	118.0
Land occupation	EURO2003	24.3	24.3	24.3
Irrigation	EURO2003	-	449.0	255.0

Table A4. Results of the uncertainty analysis with use of the Monte Carlo simulation.

Impact Categories	Unit/ton	Rainfed		Farmer-Led Irrigation		DSS Irrigation	
		5%	95%	5%	95%	5%	95%
Climate change, long term	kg CO_2 eq (long)	501.7	658.4	347.6	461.1	336.8	459.7
Climate change, short term	kg CO_2 eq (short)	514.1	674.2	355.4	471.0	344.2	469.2
Fossil and nuclear energy	MJ deprived	2334.8	2967.1	1820.5	2301.4	1586.3	2011.6
Freshwater acidification	kg SO_2 eq	5.98×10^{-6}	7.80×10^{-6}	3.64×10^{-6}	4.71×10^{-6}	3.47×10^{-6}	4.51×10^{-6}

Table A4. *Cont.*

Impact Categories	Unit/ton	Rainfed		Farmer-Led Irrigation		DSS Irrigation	
		5%	95%	5%	95%	5%	95%
Freshwater ecotoxicity	CTUe	25,817.3	33,174.8	13,029.8	16,721.5	13,422.8	17,238.2
Freshwater eutrophication	kg PO_4 P-lim eq	0.046	0.06159	0.022	0.02971	0.023	0.03123
Human toxicity, cancer	CTUh	4.10×10^{-7}	5.24×10^{-7}	2.70×10^{-7}	3.43×10^{-7}	2.50×10^{-7}	3.18×10^{-7}
Human toxicity, non-cancer	CTUh	2.22×10^{-5}	2.85×10^{-5}	1.47×10^{-5}	1.87×10^{-5}	1.36×10^{-5}	1.74×10^{-5}
Ionizing radiations	Bq C-14 eq	2874.0	3650.7	1706.5	2162.1	1642.7	2084.7
Land occupation, biodiversity	m^2 arable land eq .yr	41.36	51.4	18.94	26.1	19.43	26.5
Land transformation, biodiversity	m^2 arable land eq	0.197	0.25	0.098	0.12	0.102	0.13
Marine eutrophication	kg N N-lim eq	0.222	0.30	0.109	0.15	0.114	0.16
Mineral resources use	kg deprived	2.855	3.6	1.409	1.8	1.466	1.9
Ozone layer depletion	kg CFC-11 eq	1.02×10^{-4}	1.27×10^{-4}	5.35×10^{-5}	0.0	5.41×10^{-5}	6.77×10^{-5}
Particulate matter formation	kg PM2.5 eq	0.272	0.4	0.130	0.2	0.137	0.2
Photochemical oxidant formation	kg NMVOC eq	1.849	2.4	0.983	1.3	0.988	1.3
Terrestrial acidification	kg SO_2 eq	1.41×10^{-2}	1.94×10^{-2}	7.34×10^{-3}	1.00×10^{-2}	7.45×10^{-3}	1.02×10^{-2}
Water scarcity	m^3 world eq	8064.491	10,261.2	20,897.163	26,349.0	13,980.649	17,576.5
Damage to human health	DALY	1.82×10^{-3}	2.39×10^{-3}	1.22×10^{-3}	1.60×10^{-3}	1.15×10^{-3}	1.54×10^{-3}
Damage to ecosystem quality	PDF·m^2·yr	455.6	597.3	342.0	447.3	308.9	410.2
Total environmental impact	EURO2003	198.4	260.8	137.9	180.9	128.6	171.5

Table A5. LCA results with the ReCiPe 2016 model.

Unit	Unit/ha	Rainfed	Farmer Irrigation	DSS Irrigation
Fine particulate matter formation	kg PM2.5 eq	1.24	0.74	0.72
Fossil resource scarcity	kg oil eq	87.92	66.23	61.51
Freshwater eco-toxicity	kg 1,4-DCB eq	27.94	18.32	17.32
Freshwater eutrophication	kg P eq	0.19	0.24	0.18
Global warming	kg CO_2 eq	398.89	327.74	246.10
Human carcinogenic toxicity	kg 1,4-DCB eq	8.20	10.64	8.27
Human non-carcinogenic toxicity	kg 1,4-DCB eq	540.80	395.60	359.67
Ionizing radiation	kBq Co-60 eq	22.56	14.56	14.05
Land use	m^2a crop eq	5.60	3.28	3.31
Marine eco-toxicity	kg 1,4-DCB eq	20.13	16.53	14.48
Marine eutrophication	kg N eq	2.20	1.12	1.17
Mineral resource scarcity	kg Cu eq	4.00	1.97	2.09
Ozone formation, human health	kg NOx eq	1.29	0.76	0.72
Ozone formation, terrestrial ecosystems	kg NOx eq	1.31	0.77	0.73
Stratospheric ozone depletion	kg CFC11 eq	5.73×10^{-3}	5.23×10^{-3}	2.80×10^{-3}
Terrestrial acidification	kg SO_2 eq	6.16	3.30	3.38
Terrestrial eco-toxicity	kg 1,4-DCB	989.15	589.35	580.90
Water consumption	m^3 consumed	7.09	214.18	127.96
Human health	DALY	1.41×10^{-3}	9.47×10^{-4}	8.49×10^{-4}
Ecosystems	species.yr	3.54×10^{-6}	2.86×10^{-6}	2.39×10^{-6}
Resources	USD2013	33.20	19.89	20.22
Single score	point (pt)	25.93	17.69	15.78

Table A6. LCA results with the EF model.

Unit	Unit/ha	Rainfed	Farmer Irrigation	DSS Irrigation
Acidification	mol H+ eq	12.2	6.0	6.3
Climate change	kg CO_2 eq	584.2	315.7	316.2
Ecotoxicity, freshwater	CTUe	24,803.8	12,084.6	12,665.4
Eutrophication, freshwater	kg P eq	0.68	0.33	0.35
Eutrophication, marine	kg N eq	52.70	25.44	26.78
Eutrophication, terrestrial	mol N eq	9.47	4.77	4.92
Human toxicity, cancer	CTUh	1.03×10^{-6}	5.04×10^{-7}	5.28×10^{-7}
Human toxicity, non-cancer	CTUh	7.79×10^{-6}	3.85×10^{-6}	4.01×10^{-6}
Ionizing radiation	kBq U-235 eq	30.548	20.75	18.99
Land use	Pt	3798.629	2146.09	1957.21
Ozone depletion	kg CFC11 eq	1.10×10^{-4}	5.79×10^{-5}	5.86×10^{-5}
Particulate matter	disease inc.	0.000	0.00	0.00
Photochemical ozone formation	kg NMVOC eq	1.984	1.03	1.05
Resource use, fossils	MJ	4172.067	2516.58	2408.72
Resource use, minerals and metals	kg Sb eq	2.46×10^{-3}	1.19×10^{-3}	1.25×10^{-3}
Water use	m^3 depriv.	22,909.296	31,260.28	23,352.64
Single score	Point	0.32	0.308	0.252

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