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Eco-Efficiency of Olive Farms across Diversified Ecological Farming Approaches

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Abstract: Eco-efficiency is commonly used as an indicator of sustainability since it expresses the efficiency with which natural resources are utilized to meet people's needs. Agriculture relies heavily on these ecological resources and by-produces significant environmental burdens, shifting the interest of researchers and policymakers toward the promotion of ecological practices. However, limited evidence exists regarding eco-efficiency across various ecological approaches like low input, conservation, and organic farming. This paper contributes to the existing literature and provides insight into the eco-efficiency of Cretan olive farms managed under different ecological approaches. Olive oil production is vital for the socio-economic sustainability of Mediterranean agriculture, a significant element of the region's culture, and the basis of the well-known "Mediterranean diet"; therefore, it is crucial to investigate eco-efficient management options for olive farmers. Data Envelopment Analysis (DEA) and a second-stage statistical analysis are employed to estimate the eco-efficiency of olive farms and investigate factors affecting it. Composite indicators for biodiversity, soil, and input management are incorporated in the eco-efficiency model. The results indicate that organic farms achieve the highest eco-efficiency scores, followed by other ecological approaches. Additionally, eco-efficiency seems to be explained by farmers' dependency on subsidies, commitment to farming activity, and environmental awareness.

Keywords: conservation farming; data envelopment analysis; ecological practices; efficiency; environmental pressures; Greece; low-input farming olive groves; organic farming

Citation: Sintori, A.; Gouta, P.; Konstantidelli, V.; Tzouramani, I. Eco-Efficiency of Olive Farms across Diversified Ecological Farming Approaches. *Land* **2024**, *13*, 72. https://doi.org/10.3390/land13010072

Academic Editors: Nir Krakauer and Eusebio Cano Carmona

Received: 9 October 2023
Revised: 4 January 2024
Accepted: 5 January 2024
Published: 8 January 2024

1. Introduction

Eco-efficiency, as defined by the Organization for Economic Co-operation and Development [1], encompasses the efficiency with which ecological resources are harnessed to fulfill human needs. It signifies a production unit's capacity to achieve economic outcomes while utilizing the minimum number of possible resources and generating minimal environmental impact, aligning with the perspective elucidated by Ehrenfeld [2]. Consequently, eco-efficiency serves as a pivotal metric for assessing both the economic and environmental performance of a production unit.

As an economic activity, agriculture profoundly relies on natural resources and intricately interacts with the surrounding ecosystem. Notably, agriculture imparts significant environmental impacts, including but not limited to loss of biodiversity, overutilization of natural resources like water, emission of greenhouse gases, soil erosion, and contamination arising from the application of agricultural inputs (refer to [3,4]). The concept of eco-efficiency holds particular relevance to the evaluation of the environmental performance of agricultural activities and has attained interest as the means to foster sustainability within the food supply chain [3,5]. In other words, eco-efficiency in the food sector can be viewed as a pathway to ensure the production of high-quality products while concurrently reducing the utilization of inputs like water, energy, soil, labor, and capital (Keating et al. [6]).

Achieving eco-efficiency in agriculture can be considered an intermediate step in achieving sustainability since it provides ways to reduce environmental pressures without compromising production [7]. However, high eco-efficiency at the farm level does not necessarily lead to the sustainability of the ecosystem, since the level of production may already be higher than what the ecosystem can sustain. Nevertheless, eco-efficiency is a useful indicator from the perspective of farm management as well as policy making and consulting. It can provide insight into farm practices that enhance both economic and environmental performance at the farm level, but also assist the design of appropriate and well-targeted policy measures that promote the cost-effective use of resources.

The global drive toward sustainable food production systems and dietary patterns is now a prominent agenda, underscored by agricultural policies, and is endorsed worldwide. As per the World Health Organization [8], a sustainable diet should enhance individual health and well-being, exhibit low environmental impact, and be accessible, affordable, safe, fair, and culturally acceptable. The "Farm to Fork Strategy" promotes transition to more sustainable diets and encourages their adoption by consumers, concurrently urging producers to embrace eco-friendly farming approaches.

The Mediterranean diet, known for its health attributes and recognized by UNESCO [9] as an intangible cultural asset, has emerged as an alternative sustainable dietary paradigm, prompting research into its environmental facets. Olive and olive oil consumption, an integral part of the Mediterranean diet, boasts numerous documented health benefits [10–12]. From a production perspective, olive cultivation constitutes a vital agricultural activity within the Mediterranean region, providing livelihoods for many families, given its commonplace inclusion in the portfolios of Mediterranean farms.

Nevertheless, olive oil production raises environmental concerns such as soil degradation and overuse of water and inputs (including fuel, pesticides, and fertilizers) [13]. Given that olive oil is advocated as part of a sustainable diet, there is a pressing need to scrutinize production practices that minimize the adverse environmental impacts of olive cultivation, and explore pathways toward its agro-ecological transition.

This study attempts to delve into the eco-efficiency of Greek olive farms across various ecological farm types. Greece is a significant olive producer with a considerable olive cultivated area of 753,161 hectares, which corresponds to a total of 147,453,249 olive trees, an average cultivation density of 196 plants/ha, and a total olive production of 255,705 tons in 2021. The regions of Crete and Peloponnese, specifically, account for over half of the country's olive cultivated area (26% and 25%, respectively) [14]. The focal point of our analysis lies in the Prefectures of Heraklion and Lasithi, both situated in eastern Crete (see Figure 1).

A paramount challenge in assessing eco-efficiency and environmental performance lies in encapsulating it with a singular aggregate indicator [3,15]. In the current study, we employ Data Envelopment Analysis (DEA) to address this challenge. DEA has been extensively adopted in agricultural economics, and it is primarily used to estimate traditional technical efficiency in farming [16–20]. Numerous studies both in Greece and internationally have employed DEA to derive the technical and economic efficiency of olive farms [21–28]. DEA's utility extends to estimating the eco-efficiency of agricultural activities, underscoring its advantages (see for example [29–36]).

In this case study, we draw inspiration from the research of Gómez-Limón et al. [37], who assessed the eco-efficiency of Spanish olive groves, by employing the methodology outlined by Kuosmanen and Kortelainen [38]. The used methodology has often been employed to estimate eco-efficiency in the recent literature ([39–42]. We also incorporate various indicators to account for the main environmental repercussions associated with olive production. Farm and farmer characteristics that explain eco-efficiency are also explored through a second-stage regression analysis (as exemplified by Urdiales et al. [43]). Our examination of eco-efficiency in olive farms encompasses diverse ecological approaches, i.e., standard/typical farms and low-input farms, organic farms as well as conservation farms. These farm types were derived using the protocols and typology defined within the LIFT

(Low-Input Farming and Territories—Integrating knowledge for improving ecosystem-based farming) project (https://www.lift-h2020.eu/ (accessed on 10 September 2023)) [44], which classifies farms according to their ecological management practices.

Figure 1. Study area in Crete: Prefectures of Heraklion and Lasithi.

Hence, the purpose of our study is threefold. First, it adds to the existing literature on the eco-efficiency of olive production, which, as already stated, is crucial, especially in the Mediterranean region, and sheds light on the factors that affect it. Second, it provides an example of how eco-efficiency scores derived with the DEA methodology can serve as a single, aggregate indicator of economic and environmental performance at the farm level. Finally, it provides results regarding eco-efficiency across diversified ecological farm types contrary to the existing literature, which mainly examines efficiency or eco-efficiency in intensive, extensive, traditional, or organic olive farms (see for example [24–27]).

The subsequent section offers a comprehensive presentation of the sample farms, the data, and the methodology central to our analysis. Key findings are synthesized in the Results section, culminating in the final sections of Discussion and Conclusions.

2. Materials and Methods

2.1. Materials

The assessment of eco-efficiency of Cretan farms draws upon data from a large-scale farm survey conducted within the LIFT Horizon 2020 Project. The purpose of the project was to identify ecological approaches to farming and assess their socio-economic and environmental performance and sustainability. For this purpose, a large-scale survey was carried out to collect farm-level qualitative and quantitative data that were not available in existing databases. The data included ecological practices and drivers of adoption of such practices as well as data on farm's technical and socio-economic characteristics.

The benefits of using this dataset in our eco-efficiency analysis lie first in the fact that it contains detailed economic and environmental performance data, at farm level, necessary for the estimation of eco-efficiency. The information available contains farming practices regarding input use (water, fuel, fertilizers, and pesticides), soil management, and biodiversity aspects that were employed to develop the environmental indicators for the eco-efficiency model, as will be explained further in this section.

An additional benefit that derives from the use of the LIFT large-scale survey data is the fact that the same dataset was used to develop a protocol for the classification of farms to diversified ecological farm types, i.e., standard (typical) farms, low-input farms, and organic and conservation farms. The definitions of these ecological approaches, as elucidated within the LIFT Project, are presented in Rega et al. [44] and are summarized in Table 1. Finally, the LIFT dataset provides additional information on the farms' and the farmers' characteristics, some of which were used in the second stage regression analysis to derive the factors that explain farms' eco-efficiency.

Table 1. Definitions of the ecological olive farm types (adopted from Rega et al. [44]).

Farm Type	Definition
Organic farming	This farm type includes farms that comply with Council Regulation 834/2007 and Commission Regulation 889/20082.
Conservation farming	A farming approach that aims to preserve the soil structure, through the implementation of appropriate tillage, crop rotation, diversification, and soil cover practices.
Low-input farming	This farm type includes farms that utilize a lower level of inputs including seeds, machinery, fertilizers, and pesticides.
Standard/typical farming	This ecological approach includes farms that cannot be classified in any of the previous farm types, since they perform poorly in all ecological indicators adopted in the LIFT protocol. The farms that belong to this ecological farm type coincide to some extent, with "conventional farms".

This original Greek LIFT dataset includes olive groves as well as vineyards. However, in the context of this specific study, our focus centers on specialized olive farms. To qualify as a specialist olive farm within our criteria, a minimum of two-thirds of the farm's total output in terms of revenues must originate from olive-related activities, particularly oil production. This criterion aligns with the farm typology framework employed in the Farm Accountancy Data Network (FADN), which categorizes farms based on their Standard Gross Margin (SGM).

The focal point of our analysis lies in the Prefectures of Heraklion and Lasithi, both situated in eastern Crete and accounting for 103,970 and 27,132 hectares of olive groves, respectively [14,45]. This region represents 17% of the country's total olive trees and contributes 22% to its overall olive production. In 2016, the number of olive farms within this area amounted to 52,707, constituting 12% of the total Greek olive farms [45]. According to the total cultivated area and the corresponding number of farms, the average farm size in the area is estimated at 2.48 hectares.

The significance of olive production in Crete is underscored by the region's climatic conditions, which are conducive to olive tree cultivation, enabling adaptability to drought and salinity. It is also noteworthy that 4% of the total olive cultivation within the area under study is managed under the organic scheme, corresponding to 4590 hectares and 1016 farms (see also Sintori et al., 2023 [46]). Additionally, 2508 farms in Heraklion and 2658 farms in Lasithi hold the AGRO2 quality certification for implementing the Integrated Management System. This management system is very common in the area under study and covers 6623 hectares of olive groves in Heraklion and 5422 hectares of olive groves in Lasithi.

The Greek LIFT sample consists of precisely 73 specialist olive farms. This sample of olive farms subsequently underwent a rigorous screening for missing data and potential outliers owing to the sensitivity of the DEA methodology to these shortcomings. Notably, 14 farms were excluded from the final sample due to missing values on significant variables like water and fuel use. The remaining 59 farms were retained for in-depth analysis.

It should be emphasized that the farm sample size of this analysis is relatively small compared to the total number of olive farms in the case study area. However, using a small sample of farms or even case study farms is not uncommon when an in-depth techno-economic analysis of farms is performed (see for example [47–51]). The available dataset used in this analysis contains detailed socio-economic and technical data obtained through face-to-face interviews with farmers, which are necessary to perform the eco-efficiency estimations. No alternative dataset with the desired characteristics was available for this analysis.

It should also be clarified that the sampling methodology used in the LIFT large-scale survey was not probabilistic but rather a snowball recruitment technique. The main purpose of the sampling methodology was to identify and map alternative ecological approaches. Therefore, experts in the Cretan olive sector were recruited to identify olive farmers who adopt different ecological farming practices. Attention was paid so that farms across the whole case study area would be interviewed. This type of sampling leads to the inclusion of various farm types but it is not representative of the sector. More ecological approaches are over-recruited to fulfill the purpose of the study, while more conventional approaches are under-recruited. This, however, provides the opportunity to derive results across alternative ecological approaches, and thus the sample used fits the purpose of the study.

The farms in our sample exhibit an average land size of 5 hectares and a mean density of 210 trees per hectare (see also Table 2). Though the sample is not representative of the sector, it is important to emphasize that the average size and density are higher than the ones derived from the data of the Hellenic Statistical Authority [45] previously presented. The average output of the sampled farms is EUR 14,539 (excluding subsidies) and the average hours of labor inputs are 2168 or 1.24 Full-Time Equivalents (1 FTE = 1750 work hours).

Table 2. Main characteristics of the sampled farms and farmers.

	Farm Characteristics			
Farm size:	5 hectares			
Average density:	210 trees			
Location:	Heraklion: 30 farms	Lasithi: 29 farms		
Irrigation:	Yes: 53 farms	No: 6 farms		
Ecological Approaches:	Organic 11 farms	Conservation 15 farms	Low-input 38 farms	Standard 19 farms
Labor inputs:	Family labor 1.1 family members on average	3.16 hired workers on average		
Characteristics of farmers				
Gender of farmer	Male 44 individuals	Female 15 individuals		
Average age of farmer:	53 years			
Average experience in agriculture:	32 years			
Education level:	Primary education 7	Middle or high school education 29	Higher education 23	

The sample of specialist olive farms is nearly evenly split between the two Prefectures under investigation, with 30 of them located in Heraklion and 29 in Lasithi. Geographically, these farms predominantly occupy agricultural land at lower altitudes, specifically below 600 m, and 28 of them report land situated at altitudes lower than 300 m. The average age of the plantations of farms is quite high (41 years, excluding 4 farms with very old trees). A majority of these farms (53 out of 59) employ some type of irrigation in their agricultural practices. The main reported type of irrigation is drip irrigation (27 farms), while the remaining farms employ other types of irrigation. The most popular water sources are the mains water supply (36 farms) as well as groundwater source (24 farms). The main variety used in the sample farms is the Koroneiki variety for the production of olive oil.

Turning our attention to their ecological classification, our analysis reveals that 11 farms adhere to organic farming practices, 15 fall within the conservation farms category, while 38 are categorized as low-input farms and 19 as standard/typical farms, based on the LIFT survey's protocol for farm typology [44]. Concerning the main structural characteristics of the farms belonging to these alternative farm types, it is important to emphasize that no statistically significant differences are identified, using the Mann–Whitney test [52], regarding farm size, among the farm types, with the exception of conservation farms that are larger (average size 6.68 hectares). Age of the plantation differs only in the case of organic farms that utilize older trees. Organic farms also differ in the utilization of drip irrigation. Only 36% of the organic farms use drip irrigation compared to 46% of the total sampled farms. It is also important to note that according to the LIFT farm typology, the farm types are not mutually exclusive, with the exception of standard farming. This means that a farm may belong to more than one farm type if it meets the designated criteria. The classification of the 59 farms of our analysis is graphically presented in Figure 2, where overlaps are depicted.

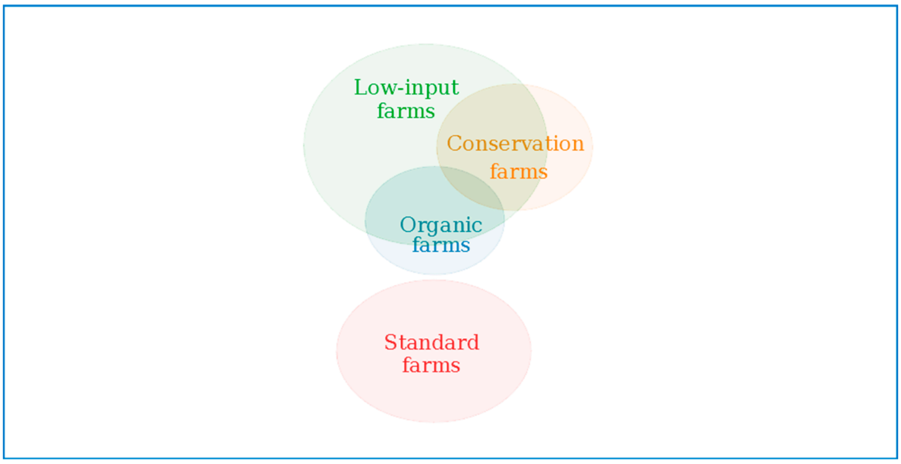

Figure 2. Ecological farm types of the Cretan olive farms. Overlap occurs between ecological farm types, in accordance to the LIFT protocol.

Demographically, the owners of these specialist olive farms are predominantly male, numbering 44 individuals. The average owner age is 53 years, with 13 of the farm owners in our sample being older than 65 years. The farmers in our sample have on average 32 years of experience in the agricultural occupation. Furthermore, 23 of them have attained higher education qualifications, while 29 have completed either middle school or high school. It is noteworthy that 12 of these individuals have received agricultural high school or university education.

With regard to work inputs, a substantial portion, namely, 75%, is contributed by family members, with an average of 1.1 family members actively engaged in the olive farming business. Additionally, some of these farms also employ hired workers, primarily on a seasonal basis, tasked with activities such as olive harvesting and tree pruning.

Almost half of the olive farms in our sample use hired workers while one-third of these farms use more than 3 hired seasonal workers for these duties. Remarkably, despite their specialization in olive production, pluriactivity is a common practice among these farmers. It is estimated that on average, over 60% of the total household income derives from sources outside agriculture.

Furthermore, it is noteworthy that the surveyed farmers exhibit a pronounced inclination toward well-being and environmental objectives. During the LIFT farm survey, participants were asked to evaluate, on a 5-point Likert scale, a set of objectives, to identify potential drivers of the adoption of ecological practices. Notably, objectives such as "Protecting the environment for future generations", "Farming in a way that enhances the environment", and "Improving the condition of land" received very high ratings from the olive farmers in our sample (mean values of 4.34, 4.29, and 4.22, respectively). Conversely, common economic objectives, such as "Maximizing profit", received lower scores from Greek olive producers (mean value 3.88). These objective statements rated within the LIFT survey can be examined in our analysis as potential explanatory factors of eco-efficiency.

Lastly, regarding the distribution channels that the olive farms of our sample prefer, producers' organizations receive an average of 43% of the production, followed by merchants (24% on average) and processors (14% on average). A minor proportion of the production is directly marketed from farmers to consumers (9% on average).

2.2. DEA Analysis

To evaluate the economic and environmental performance of the sample olive farms, we employ the eco-efficiency concept and the estimation methodology originally introduced by Kuosmanen and Kortelainen [38] and subsequently adopted in numerous studies focusing on agricultural pursuits [29,30,43,53,54]. Kuosmanen and Kortelainen [38] advocate the use of DEA as a means to aggregate environmental pressures into a unified eco-efficiency indicator. DEA, initially formulated by Charnes et al. [55], is a non-parametric technique employed for technical efficiency estimation. The essence of DEA lies in constructing a production frontier, consisting of all decision-making units (DMUs)—farms in our study—which produce a specific output with minimum inputs. These DMUs are identified as benchmark units. Deviations from the constructed frontier, consisting of the efficient DMUs, signify inefficiencies.

Let N represent our sample of DMUs, i.e., olive farms, V_n denote the economic value added and Z_n denote the environmental pressures of each individual unit n ($n = 1, 2, \ldots, N$). Eco-efficiency can then be defined as the following ratio [38]:

$$EE_n = \frac{V_n}{D(Z_n)} \quad (1)$$

Here, D represents the damage function, which aggregates the m environmental pressures into a unified environmental damage score, as stipulated by Kuosmanen and Kortelainen [38]. A linear expression of D is the following:

$$D(z) = w_1 z_1 + w_2 z_2 + \cdots + w_M z_M \quad (2)$$

In this linear expression of D, w_m ($m = 1, \ldots, M$) signifies the weight assigned to the environmental pressure m. By implementing DEA, we ascertain the weights that maximize the efficiency score for each DMU [29,38,43]:

$$\max EE_n = \frac{V_n}{w_1 Z_{n1} + w_2 Z_{n2} + \cdots + w_M Z_{nM}}$$

subject to

$$\begin{gathered}\frac{V_1}{w_1 Z_{11} + w_2 Z_{12} + \cdots + w_M Z_{1N}} \leq 1 \\ \frac{V_2}{w_1 Z_{21} + w_2 Z_{22} + \cdots + w_M Z_{2N}} \leq 1 \\ . \\ . \\ . \\ \frac{V_N}{w_N Z_{N1} + w_2 Z_{N2} + \cdots + w_M Z_{NM}} \leq 1 \\ w_1, w_2, \ldots, w_M \geq 0\end{gathered} \tag{3}$$

It is noteworthy that the constraints above impose a maximum eco-efficiency value of one (100%). The value is also bounded from below by 0, considering that the weights are non-negative. Higher values denote superior environmental performance, while values closer to zero signify increased eco-inefficiency. Addressing the computational challenges associated with this non-linear problem, we can instead minimize the inverse of the eco-efficiency ratio [38]:

$$\min EE_n^{-1} = w_1 \frac{Z_{n1}}{V_n} + w_2 \frac{Z_{n2}}{V_n} + \cdots + w_M \frac{Z_{nM}}{V_n}$$

subject to

$$\begin{gathered}w_1 \frac{Z_{11}}{V_1} + w_2 \frac{Z_{12}}{V_1} + \ldots + w_M \frac{Z_{1M}}{V_1} \geq 1 \\ w_1 \frac{Z_{21}}{V_2} + w_2 \frac{Z_{22}}{V_2} + \ldots + w_M \frac{Z_{2M}}{V_2} \geq 1 \\ . \\ . \\ . \\ w_1 \frac{Z_{N1}}{V_N} + w_2 \frac{Z_{N2}}{V_N} + \ldots + w_M \frac{Z_{NM}}{V_N} \geq 1 \\ w_1, w_2, \ldots, w_M \geq 0\end{gathered} \tag{4}$$

The eco-efficiency score derives from the inverse of the optimal solution of this linear problem. It is essential to underscore that the DEA eco-efficiency scores are used to derive the maximum proportional reduction in the m environmental pressures that can be technically achieved given the level of economic output denoted by V.

As Kuosmanen and Kortelainen [38] emphasize, these DEA scores assigned to each eco-inefficient farm offer guidance on potential efficiency enhancements. These improvements might pertain to the practices a farm should adopt or the adjustments it needs to make to approximate the performance of efficient farms.

It should also be noted that the methodological framework of Kuosmanen and Kortelainen [38] implies constant returns to scale (CRS). Although, in farming, economies of scale are important, and they are considered a variable returns to scale (VRS) activity, Gómez-Limón et al. [37] and Picazo-Tadeo et al. [29] argue that from an environmental perspective, farming can be considered a constant returns to scale activity. They also point out that in an eco-efficiency analysis, what is important is to estimate the eco-inefficiency of farms, regardless of whether this can be attributed to suboptimal management or farm size.

As we already mentioned, within our analysis, we employ the methodological framework of Kuosmanen and Kortelainen [38] and draw inspiration from the work of Gómez-Limón et al. [37], who also use the same conceptual framework to estimate the eco-efficiency of Spanish olive groves. Gómez-Limón et al. [37] identify six environmental pressures that they use in their DEA model, which refer to soil erosion, biodiversity, pesticide risk, water use, nitrogen ratio, and energy ratio as a proxy for Greenhouse Gas Emissions. In our analysis, we employ four similar indicators that are used as variables in the DEA model, representing the environmental pressures. These variables include two simple indicators corresponding to water and fuel utilization, as well as two composite indicators that aggregate soil and biodiversity management practices as well as fertilization and pest management practices. The calculation of the indicators is described in detail in this section (see also Table 3):

1. Water utilization. Irrigation water usage is a significant environmental concern linked to agricultural activities. This concern is particularly relevant in the region of Crete, where water scarcity issues prevail, exacerbated by anticipated climate-induced changes in precipitation patterns [56]. Although olive cultivation historically relies on rainfed practices and is not considered particularly water-intensive, evolving climate dynamics and emerging intensification emphasize the criticality of sound water management practices. It is therefore crucial to include water utilization as an environmental pressure indicator similar to the work of Gómez-Limón et al. [37].
2. Fuel utilization. Fuel utilization denotes the consumption of an important resource and can also be used as a proxy for greenhouse gas emissions (GHGs) from on-farm activities (see also [57]). It should be noted that this is only part of the GHGs linked to olive cultivation, as other sources like pre-chain emissions are not considered in this study due to unavailable data regarding specific types of inputs. Notably, fuel constitutes the primary energy source within olive farms, often leading to elevated consumption levels due to the fragmented land structure of Greek holdings.
3. Soil and biodiversity management. This indicator, sourced from the LIFT survey-based farm typology protocol [44], integrates various soil and biodiversity-related management practices within olive farms. These practices encompass soil tillage intensity (ranging from conventional tillage to conservation tillage and no tillage), crop rotation, and diversification practices as well as soil cover practices (including planting of cover, catch, and N-fixing crops and leaving crop residues on soil). Each practice is incorporated as a binary variable (1 if implemented, 0 otherwise). A basic score is assigned to each variable/practice according to the environmental significance of the practice. These basic scores were derived from experts in the field employed within the LIFT Project with this specific duty. Farm-specific information is then used to derive a weighted score for each practice. This farm-specific information is the percentage of the farm on which the practice is implemented. Thus, the weighted score derives as a product of practice-specific and farm-specific information and is therefore unique for each farm in the sample. Weighted scores are then added to derive partial scores of practices that refer to the same aspect, e.g., tillage and final scores of the "Soil and biodiversity management" index are finally derived by combining the partial scores. The detailed description of the methodology followed in the LIFT Project to estimate these indicators, including basic scores and weights, is described in the relevant documentation of Rega et al. [44]. For the use of this indicator, we were inspired by Gómez-Limón et al. [37], who used a very similar composite indicator

for biodiversity, constructed as a weighted sum of binary variables that represent the degree of implementation of specific practices that enhance biodiversity, like soil cover. As Gómez-Limón et al. [37] emphasize the weights assigned to each practice for the construction of their composite indicator derived from experts, it should be noted that higher values of the "Soil and biodiversity management" index used in the present study reflect superior soil quality and biodiversity enhancement practices. In order to denote environmental pressure, the inverse of the indicator can be considered. Data transformation is common in studies using DEA analysis to estimate environmental efficiency and is employed to deal with undesirable outputs [58,59].

4. Fertilization and pest management. This indicator was also developed using the LIFT survey-based farm typology protocol. It encompasses fertilizer usage practices such as the application of inorganic fertilizer, animal manure, green manure, compost, and other soil amendments. Pest control practices are also included in the formation of this indicator, including employment of chemical pesticides or other products authorized in organic farming, application of integrated pest management, or other pest control practices like weeding. Similar to the previous indicator, the weights attached to each practice for the calculation of this composite indicator are derived from a combination of expert opinion and area of application within the farm (for a detailed presentation of the calculation of this indicator refer to Rega et al. [44]). Additionally, the application of these inputs at lower than the recommended dosage is taken into consideration. As before, higher scores of this indicator denote better management from an ecological point of view.

Table 3. Explanation of the variables incorporated in the eco-efficiency analysis.

Environmental Indicators	
Water utilization	Irrigation water used (in m^3/ha)
Fuel utilization	Fuel used to perform farm tasks (in lt/ha)
Soil and biodiversity management	Composite indicator of soil and biodiversity management practices
Fertilization and pest management	Composite indicator that includes fertilization and pest management practices
Economic Indicator	
Net income	Revenues (excluding subsidies) minus direct costs (fuel, seeds, fertilizers, pesticides, soil amendments, contract labor, and other variable costs) (in EUR/hectare)

2.3. Truncated Regression Analysis

The subsequent phase of our analysis entails a second-stage regression examination, specifically a truncated regression analysis, conducted to explain the eco-efficiency scores derived from the DEA methodology, using specific attributes pertaining to the farm and its operator. The truncated regression analysis, as demonstrated also in previous studies (e.g., [54]), employs a set of explanatory variables for eco-efficiency. The variables used in this analysis, encompass demographic characteristics of the farmer (e.g., education, gender, and age), attributes pertinent to the farmer's economic activities (e.g., farm size subsidy independence, income sourced from olives and farming, and family members' engagement to the activity) as well as farmer's objectives and attitudes (e.g., profit maximization and protecting the environment). The explanatory variables used in our analysis are presented in Table 4, together with a brief description of their definition and indicative literature on studies that explore similar variables as determinants of eco-efficiency.

The preference for truncated regression analysis, over Ordinary Least Squares (OLS) regression, stems from the truncated nature of the dependent variable, consisting of the efficiency scores. Estimations conducted through OLS regression are deemed biased and inconsistent due to this feature of the dependent variable [60]. Consequently, truncated regression models, which are generally preferred and deemed more appropriate, are usually employed to explain eco-efficiency [61–63]. Both the statistical and DEA analyses were executed using STATA/SE 13.0.

Table 4. Explanation of variables used in the truncated regression analysis.

Variable	Definition	Indicative Literature
Farm size	Farm-utilized land in hectares	Picazo-Tadeo et al. [7]
Subsidy independence	The ratio of revenues to revenues including subsidies	Godoy-Durán et al. [53]; Eder et al. [33]
Education	Ordinal variable with values: 1 for primary education, 2 for Middle school, and High school education, 3 for Higher education	Godoy-Durán et al. [53]; Gómez-Limón et al. [64]
Gender	Binary variable with values: 1 for male, 0 otherwise	
Age < 40	Binary variable with values: 1 if the owner is younger than 40 years, 0 otherwise	Godoy-Durán et al. [53]; Gómez-Limón et al. [64]; Urdiales et al. [43]; Eder et al. [33]
Age > 65	Binary variable with values: 1 if the owner is older than 65 years, 0 otherwise	Godoy-Durán et al. [53]; Gómez-Limón et al. [64]; Eder et al. [33]
Income from olives	Proportion of farm income that stems from olive cultivation (%)	Godoy-Durán et al. [53]; Urdiales et al. [43]
Income from farming	Proportion of household income that stems from farming (%)	Gómez-Limón et al. [64]; Eder et al. [33]
Household members working on the farm	Number of members of the household that work on the farm	Godoy-Durán et al. [53]
Maximizing profit	Ordinal variable indicating importance of economic objective (measured on Likert scale: 1 = not at all important, 2 = Unimportant, 3 = Neither important nor unimportant, 4 = Important, 5 = Very important)	Urdiales et al. [43]; Türkten and Ceyhan [65]
Protecting the environment for future generations	Ordinal variable indicating importance of environmental objective (measured on Likert scale: 1 = not at all important, 2 = Unimportant, 3 = Neither important nor unimportant, 4 = Important, 5 = Very important)	Urdiales et al. [43]; Türkten and Ceyhan [65]

3. Results

3.1. Descriptive Statistics of the DEA Data

Table 5 provides a comprehensive statistical summary of the variables that are used to estimate eco-efficiency, in the current study. Water and fuel utilization per hectare as well as net income per hectare are presented for every ecological approach as well as for all farms in the sample. The two composite indicators constructed to summarize soil and biodiversity practices and fertilization and pest management practices are also presented in the table. It should be noted that, as previously stated, high scores of the composite indicators present better management from an ecological point of view. The inverse of these indicators is in fact used to denote environmental pressures.

The results presented in Table 5 underscore the need to employ an aggregate indicator for estimating the eco-efficiency of the sampled farms, as previously discussed. Examination of the average values and standard deviations of the variables used in the analysis reveals significant variations across ecological farm types. Thus, these alternative ecological approaches exhibit varying performance with regard to each environmental indicator.

As can be seen in Table 5, low-input and standard farms utilize less water, therefore causing less pressure on this natural resource. Water utilization, on the other hand, is significantly higher in the organic farms of our sample, which perform better in other indicators, i.e., soil and biodiversity management as well as fertilization and pest management. Organic farms also use higher fuel inputs compared to other ecological farm types, possibly to perform various tasks like machine weeding. Fuel utilization appears to be smaller in low-input and standard/typical farms. Organic and low-input farms also perform well in the "Soil and biodiversity management indicator". Standard farms, on the other hand, appear to have lower scores regarding the "Fertilization and pest management" indicator and the "Soil and biodiversity management indicator", but consume less water and fuel.

Table 5. Main statistics of the economic and environmental indicators across ecological approaches.

	Water Utilization (m^3/ha)	Fuel Utilization (lt/ha)	Soil and Biodiversity Management (Dimensionless)	Fertilization and Pest Management (Dimensionless)	Net Income (EUR/ha)
Ecological approaches	Mean (st. Deviation)				
Standard farming	425 (533)	159 (158)	1.25 (0.43)	2.10 (0.26)	1402 (1344)
Conservation farming	571 (498)	237 (224)	2.71 (0.27)	3.01 (0.32)	1484 (1749)
Organic farming	635 (743)	345 (328)	1.81 (0.60)	3.00 (0.49)	2110 (1670)
Low-input farming	542 (545)	218 (239)	1.90 (0.77)	3.01 (0.23)	1700 (1650)
Total farms	517 (553)	211 (227)	1.68 (0.75)	0.68 (0.50)	1559 (1539)

Another important finding presented in Table 5 lies in the case of conservation farms. These farms, by definition, perform better in the "Soil and biodiversity management" indicator. They also perform well in terms of the "Fertilization and pest management" indicator, but seem to overconsume irrigation water and fuel.

With regard to net income, we should note that it is higher in organic and low-input farms. Reasons for this could be the lower costs for inputs or the price premium received for high-quality olive oil.

The main assumption deriving from the data in Table 5 is that the overall environmental and economic performance of farms belonging to each ecological approach remains elusive without the use of a single-aggregate indicator, which, in this study, is represented by the DEA-produced eco-efficiency score.

3.2. Results of the DEA Analysis

Let us now shift our focus to the examination of the eco-efficiency performance of the sampled farms that derived from the application of the DEA methodology. Table 6 summarizes the main findings of this analysis. The calculated average eco-efficiency is apparently low, estimated at 0.34, leaving room for substantial improvement. Notably, organic farms emerge as being more eco-efficient compared to other farm types, followed by conservation and low-input farms. Standard farming on the other hand demonstrates very low eco-efficiency scores, largely attributed to their poor performance in the "Fertilization and pest management indicator as well as the "Soil and biodiversity management" indicator. The results indicate that, as expected, more agro-ecological farming types exhibit higher eco-efficiency scores than standard farming, but the fact remains that even these farms still appear to have low eco-efficiency. Specifically, only five farms in the sample have an eco-efficiency score of 1, forming the eco-efficiency frontier, and four more farms have eco-efficiency scores higher than 0.8. Three of the eco-efficient farms (score of one) and three of the farms with an eco-efficiency score higher than 0.8 are characterized as low-input, while, on the other hand, only one standard farm is characterized as eco-efficient. The Mann–Whitney test [52] performed in STATA and the Steel–Dwass test performed in Jamovi (https://www.jamovi.org/ (accessed on 21 December 2023) were used to identify statistically significant differences in eco-efficiency among farm types. Only, in the case of low-input farms are statistical differences identified ($p < 0.1$).

Table 6. Main statistics of Eco-efficiency per ecological farm type.

Ecological Farm Type	Mean	Standard Deviation	CV	Min	Max
All farms	0.34	0.31	91%	0.01	1
Organic	0.46	0.35	76%	0.03	1
Conservation	0.40	0.32	80%	0.06	1
Low-input	0.40	0.32	80%	0.03	1
Standard/typical	0.28	0.28	100%	0.01	1

3.3. Results of the Truncated Regression Analysis

The obtained eco-efficiency scores underwent additional scrutiny through truncated regression analysis. The results, presented in Table 7, reveal several noteworthy findings. Notably, subsidy independence exerts a positive and statistically significant effect on eco-efficiency, evident from the coefficient and p-value of this variable. This implies that subsidies may in fact cause eco-inefficiency, or in other words, farms that depend less on subsidies and derive their income from the market value of their products achieve better performance in terms of eco-efficiency.

Table 7. Results of the Truncated Regression analysis.

Variables	Main Variable Statistics	Results of the Truncated Regression Analysis			
		Log likelihood = 29.9724 Prob > chi^2 = 0.00	Wald chi^2(10) = 3619		
		Coefficient	Std. Err.	z	p > z
Farm size	Mean (St.dev): 5.03 (3.75)	0.0078441	0.0194334	0.4	0.686
Subsidy independence	Mean (St.dev): 0.77 (0.18)	2.462842	0.3984955	6.18	0.000
Education	Mean (St.dev): 2.29 (0.64)	0.1340843	0.1265764	1.06	0.289
Gender	Frequencies: Female: 15, Male 44	0.4480702	0.1803677	2.48	0.013
Age < 40 years	Frequencies: 8 individuals	0.1114533	0.2452697	0.45	0.650
Age > 65 years	Frequencies: 13 individuals	−0.1676241	0.1887549	−0.89	0.375
Income from olives	Mean (St.dev): 96% (9%)	0.6501602	0.7816457	0.83	0.406
Income from farming	Mean (St.dev): 34% (33%)	0.0068787	0.0022343	3.08	0.002
Household members working on the farm	Mean (St.dev): 1.1 (1.2)	0.1088122	0.0608112	1.79	0.074
Maximizing profit	Mean (St.dev): 3.88 (1.4)	−0.1434571	0.0736946	−1.95	0.052
Protecting the environment for future generations	Mean (St.dev): 4.33 (1.52)	0.2947688	0.031953	9.23	0.000
Constant		−4.353872	0.7994709	−5.45	0.000
sigma		0.314392	0.0004495	699.5	0.000

Additionally, the education level of the farmer appears to influence farm eco-efficiency in a positive way, though the effect is not statistically significant. As already discussed, 23 farm owners have attended higher education, in some cases, related to agriculture. Gender is another factor that affects eco-efficiency scores that should be elaborated. The results indicate that male farm owners tend to exhibit a more eco-efficient management. It should however be explained that, in Greece, it is common for male farmers who have other main occupation to nominate their wives as farm owners, even in cases where the management still remains in their hands. Thus, this finding may to some extent be explained by the fact that the actual manager of the farm is only a part-time farmer. However, further investigation is required to interpret this result.

Furthermore, it is important to highlight that a higher percentage of income derived from farming is correlated with greater eco-efficiency. In other words, farmers deeply engaged in farming activities tend to garner higher eco-efficiency scores. On the other hand, the percentage of farm income attributed to olive cultivation seems to have no statistically significant effect on eco-efficiency scores, keeping in mind that the farms of our sample derive the majority of their income from olive cultivation. This finding should be further investigated in the future, with the participation of farms with a wider portfolio and a smaller presence of olive monoculture. The results of the regression analysis also reveal that the number of household members that offer their work on the farm has a positive impact on efficiency. This means that the "family" business model, predominant in Greek agriculture, may offer fertile ground for the transition to more agro-ecological farming practices.

Finally, regarding farmers' attitudes and objectives, the results of the analysis reveal that placing more value and rating the environmental objective higher is positively correlated with eco-efficiency scores. On the contrary, it appears that placing emphasis on profit maximization may in fact have a negative impact on eco-efficiency. This is an indication that the main driving force behind the adoption of more eco-efficient approaches and ecological practices may be the environmental concern and awareness of farmers.

4. Discussion

Eco-efficiency serves as a valuable metric for estimating the environmental performance of agricultural activities, and though it does not guarantee the sustainability of the agro-ecosystem, it certainly presents a step in the right direction. Eco-efficiency signals paths to sustain consistent output levels while concurrently minimizing environmental pressures. In this sense, it is a useful concept for policymakers, since it combines their goals of securing sufficient production to meet consumers' needs and addressing critical environmental challenges.

This study centers on estimating the eco-efficiency of Greek olive groves operating on the island of Crete, taking into consideration their primary farming practices, which relate to water and fuel utilization, fertilization, and pest management, as well as soil and biodiversity management. The DEA methodology, traditionally used to determine the technical efficiency of production units, is employed to estimate individual farm eco-efficiency. This approach allowed the utilization of the scores derived from the DEA methodology as a single composite indicator of the eco-efficiency of olive farms, simplifying the environmental assessment process compared to employing multiple individual indicators. Additionally, the analysis incorporates the degree of agro-ecologization of farms, presenting results for the entire olive farm sample, as well as disaggregated results for organic, conservation, low-input, and standard (conventional) farming.

The results of our analysis denote what is already well emphasized by Kuosmanen and Kortelainen [38], that the use of single environmental indicators, like, for example, water utilization, fails to consider the potential for substitution between environmental pressures and natural resources. Thus, it cannot provide an answer for overall environmental performance at the farm level, complicating the task for policymakers and advisors. In our analysis, it is evident that all environmental indicators have to be simultaneously considered to provide a conclusive answer regarding the overall performance of farms.

Specifically, the findings of this analysis reveal that certain farm types excel in specific environmental indicators while performing poorly in others. For example, organic farming performs better as far as biodiversity and soil management are concerned, as well as fertilization and pest management, but utilizes more water and fuel compared to other ecological approaches. Similarly, conservation farming employs better biodiversity and soil management practices but performs poorer in terms of water usage.

One explanation for the higher water inputs of the organic farms in our sample is the type of irrigation used. As already mentioned, 46% of all farms utilize drip irrigation, which is considered more efficient with regard to water use. But only 36% of the sampled organic farms use drip irrigation, though almost all of them (with the exception of one farm) use some type of irrigation. The percentage of drip irrigation is higher in the case of standard and low-input farms, which appear to utilize less water. In the case of fuel consumption, the higher use of fuel in organic farms may be justified by the fact that these farms perform mechanical tasks like weeding at a higher frequency, compared to other farm types that use other inputs, e.g., herbicides. It should be emphasized, however, that the study refers to on-farm fuel consumption and does not take pre-chain fuel use into consideration, i.e., the fuel used for the production of inputs.

The DEA methodology aggregated all environmental pressures in one eco-efficiency score, which also considered economic performance in terms of net income. This way, both economic and environmental performance is taken into consideration, so that agricultural output and farmers' economic well-being is not compromised by the use of inefficient ecological practices. The average eco-efficiency score that the analysis produces is quite low and equals 0.34, ranging from 0.46 for organic farms to 0.28 for standard farms.

The low eco-efficiency of olive groves is also identified in the studies of Gómez-Limón et al. [37] and Beltrán-Esteve et al. [24], which focus on Spanish agriculture. The first study suggests that eco-inefficient olive farms generate environmental pressures that are 262% higher than the pressures produced by eco-efficient farms. Beltrán-Esteve et al. [24] estimate that the environmental pressures of Spanish olive farms can be reduced by 45–49% (depending on the farm type) while maintaining the same level of output.

In these studies, eco-inefficiency is higher than the technical inefficiency estimated in a number of studies focusing on olive groves in the Mediterranean basin [21–23,25–28]. Our analysis also yields lower eco-efficiency scores, compared to technical efficiency scores estimated for Greek olive farms in previous studies (see for example Sintori et al. [46]). Tzouvelekas et al. [66] estimated that the mean technical efficiency of conventional olive groves in Greece is 0.54, which still leaves room for improvement in input utilization, but is higher than the mean eco-efficiency estimated in our analysis.

Indeed, as the technical efficiency concept would suggest, the mean eco-efficiency signifies the maximum proportionate reduction in environmental pressures attainable, considering also output (in our case net income). The results of our analysis indicate that a 66% reduction in environmental pressures is feasible, while maintaining the same level of output. In the context of eco-efficiency analysis, a slightly different interpretation appears more fitting [38]. The individual eco-efficiency scores reveal necessary improvements and management adjustments a farm should opt for to approximate the performance of efficient farms. For instance, combining data from Tables 5 and 6 suggests that organic farms could potentially enhance their performance by implementing more efficient water and fuel management practices, e.g., precision irrigation. Conversely, standard farms might consider improving their fertilization and pest management practices, as well as soil and biodiversity management practices, which will also have a positive impact on their costs and economic benefits. It should be emphasized that net income is relatively small in all farm types, which may be an additional eco-inefficiency factor. This is partially explained by the fact that the data used in the analysis refer to the year 2018, which was a somewhat challenging year for olive production, since yields were to some extent compromised by pests and weather conditions.

Many noteworthy results derive also from the second-stage regression analysis. These results indicate that subsidies, which are considered significant for the economic sustainability of farms, such as in the case of organic farms, exert a negative influence on eco-efficiency, while farms that are more market-oriented achieve a higher eco-efficiency level. Similar conclusions regarding the impact of subsidies on farm environmental performance have been reached in other studies [67], as well as in investigations focusing on the technical efficiency of olive groves in the Mediterranean [68,69]. The above findings have important implications for agricultural planning and policymaking, in the sense that subsidies, though necessary for economic results, should be applied coupled with other environmental policy measures and incentives.

The demographic characteristics of farmers also impact eco-efficiency scores. A higher education level has a positive though not statistically significant effect on eco-efficiency, since it allows farmers to adopt cost-effective and environmentally friendly management practices. The positive effect of education on the environmental performance of farms is pronounced in numerous studies exploring eco-efficiency (refer to [29,53,70]).

Furthermore, commitment to the farming activity, as the main occupation and income source, seems to have a positive effect on eco-efficiency. This finding is consistent with research by Gómez-Limón and Sanchez-Fernandez [64], which suggests that agricultural sustainability improves as income from farming increases.

Additionally, older farmers seem to employ rather eco-inefficient management, according to the results of the regression analysis, though age is not statistically significant in our case study. These are mainly traditional farmers who usually practice standard farming and may not realize the impact of their activities on the environment or may lack environmental training and awareness. In this case, the eco-efficiency of olive farms may improve in the future as these farmers exit the activity.

Finally, it appears from the results of the regression analysis that the attitudes and objectives of farmers play an important role in achieving eco-efficiency. Environmental concerns seem to be important drivers for adopting environmentally friendly farming practices that increase the performance of the farms in soil management, promotion of biodiversity, and input use and, in turn, increase eco-efficiency. On the other hand, maintaining excessive focus on profit may in fact yield negative results on a farm's overall economic and environmental sustainability.

The results of the analysis denote the importance of designing and implementing targeted training courses on the application of ecological practices, as a prerequisite for the improvement of eco-efficiency at the farm level. Among the other direct benefits that arise from educating farmers on cost-effective ways to manage their farms, such as decreased input costs, appropriate training will increase the environmental awareness of farmers, yielding long-term benefits on eco-efficiency and sustainability.

5. Conclusions

Achieving environmental sustainability in agriculture is highlighted in the Common Agricultural Policy and is a primary goal of policymakers, especially, in light of rapid climate change. However, assessing the environmental performance at the farm level in a clear, comprehensive, and concise way is a rather challenging task.

Our study provides an example of how the DEA methodology can be used to aggregate all the environmental pressures of a farming activity into one composite indicator, which is eco-efficiency, and that also takes economic results into account. The study also contributes to the existing literature on eco-efficiency, in that it presents the latter for diversified ecological approaches, i.e., organic, conservation, low-input, and standard farms. The analysis focuses on Greek olive farms and finds that they demonstrate low eco-efficiency scores and that there is a lot of room for improvement.

However, it is essential to emphasize that further research is required to delve deeper into eco-efficiency scores and their determinants. One limitation of the current analysis is that it utilizes data obtained in the year 2018, which was characterized as a relatively low-yield year in olive production, and from a small sample of farms, not representative of the sector. Using data from additional reference years and expanding the sample to include all farm sizes would help confirm the derived results and correct any bias stemming from these limitations. Using alternative methodologies to estimate eco-efficiency, e.g., slack-based measure DEA models (SBM) (see for example [71,72]) can also provide an alternative way to verify results. The role of farmers' objectives and attitudes warrants further investigation, particularly given the observation that eco-efficiency scores are positively impacted by objectives related to environmental protection. Future research may also involve a wider range of agricultural activities, apart from olive production, which will expand knowledge on the effect of ecological approaches, like crop diversification, on eco-efficiency and sustainability. Additionally, other environmental pressures like soil retention of chemical fertilizers and waste can be considered provided the availability of data.

Overall, the analysis may prove useful for policymakers in the design of measures that promote appropriate ecological approaches adapted to certain activities and region-specific environmental concerns. It is evident from the results of this study that alternative ecological approaches perform differently in the various ecological indicators. Taking these results into consideration in agricultural policy may lead to the design, promotion, and implementation of area-appropriate eco-schemes based on the limitations of the natural resources, e.g., water, or the main environmental problems of the specific area, e.g., soil erosion.

Author Contributions: Conceptualization, A.S.; methodology, A.S.; software, A.S. and P.G.; validation, A.S., P.G., V.K. and I.T.; formal analysis, A.S. and P.G.; investigation, A.S. and P.G.; resources, I.T.; data curation, A.S. and V.K.; writing—original draft preparation, A.S. and P.G.; writing—review and editing, V.K. and I.T.; visualization, A.S.; supervision, A.S. and I.T.; project administration, I.T.; funding acquisition, I.T. All authors have read and agreed to the published version of the manuscript.

Funding: This study is part of the LIFT ('Low-Input Farming and Territories—Integrating knowledge for improving ecosystem-based farming') project that has received funding from the European Union's Horizon 2020 research and innovation program under Grant Agreement No 770747.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions.

Acknowledgments: The authors would like to thank the experts, interviewers, and respondents for their collaboration during the implementation of the LIFT Project survey. The authors would also like to thank Angelos Liontakis for his valuable recommendations on early drafts of this paper.

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

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