Promoting ecosystem and human health under climate change

——An integrated analysis of sustainable olive cultivation in Cyprus

by

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Abstract

Achieving agricultural sustainability has become a high priority to ensure society's current and future food needs without compromising ecosystem health, economic profitability, and human well-being. Organic agriculture has been proposed as an alternative to conventional farming for meeting sustainable goals. However, empirical evidence linking organic farming, human health, and sustainability in the context of climate change is scarce. In addition, previous studies comparing organic and conventional agriculture have not considered the variation in farming practices within the same management regime.

In this study, a multi-criteria sustainability assessment framework with ten indicators has been developed and proposed for sustainable olive cultivation and applied to a case study in Cyprus to evaluate the economic, ecological, and human health implications of ten organic and conventional olive orchards using different management practices. Our results indicate advantages of organic olive cultivation for higher market price, soil biodiversity maintenance, less intensive pesticide application, and higher content of polyphenols in the olive oil. However, there is a large variation in sustainability performance within the same management system. In general, we suggest organic agriculture is more beneficial for ecosystem and human health compared to conventional farming, and recommend conservation practices such as no-till, intercropping, and cover cropping, as well as optimal irrigation decisions to achieve sustainable olive cultivation under semi-arid Mediterranean climate.

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1. Introduction

Despite the presumed continuing decline in the global average fertility rate, the human population is still expected to increase by 2 billion between 2020 and 2050 (UN, 2019), which will require a significantly greater amount of calories, proteins, fats, and nutrients than our current food system can support (Cheeseman, 2016). The imbalance between the escalating food demand and the limited availability of land and other natural resources is posing unprecedented challenges to our global food security and may increase its susceptibility to environmental perturbations, market volatility, and changes in energy or trade policies (Suweis *et al.*, 2015). Meanwhile, climate change is likely to exacerbate the current food insecurity, especially in regions that are already vulnerable to hunger and malnutrition (Wheeler & Braun, 2013). In addition to the changes in temperature and rainfall patterns which will affect agricultural productivity, an emerging body of evidence has indicated that climate change is decreasing the nutritional quality of various important food crops, including rice and wheat, which may add to the global burden of malnutrition and micronutrient deficiencies (Smith & Mayers, 2018). Thus, creating and maintaining an economically, socially, and environmentally sustainable and climate-resilient food system (FAO, 2018) is critical for not only feeding but also nourishing the global population and improving human well-being.

While a food system includes all processes and resources involved in producing, processing, distributing, marketing, and consuming food (Neff *et al.*, 2015), achieving agricultural sustainability is of fundamental importance to improve food security and human nutrition (Arora, 2018). However, conventional agriculture, the most prevailing agricultural system in modern times, is perceived as unsustainable. Conventional agriculture, also referred as "modern farming" or "industrial agriculture", is defined as "capital-intensive, large-scale, highly mechanized agriculture with monocultures of crops and extensive use of artificial fertilizers, herbicides and pesticides, with intensive animal husbandry" (Knorr *et al.*, 1984). The heavy reliance of conventional agriculture on synthetic fertilizers, pesticides, antibiotics, and fossil fuel, has been associated with various environmental problems, such as soil erosion, leaching of harmful chemicals, loss of biodiversity, and many other indicators of environmental degradation (Auerswald *et al.*, 2006). At the same time, conventional farming also poses potential threat to human well-being and public health for its negative impacts on farm worker safety, human nutrition, and smallholders' self-sufficiency (Primentel *et al.*, 2005).

Since the late half of the 20th century, alternative systems such as organic farming, conservation agriculture, and regenerative agriculture, have been proposed to challenge the conventional agriculture paradigm and shift towards a more sustainable agriculture (Beus & Dunlap, 1990). These alternative approaches draw from both traditional practices and scientific innovations, and often encompass certain philosophy or values that integrate land stewardship with agriculture and consider the wellbeing of future generations (Neher, 2018).

Organic agriculture, for example, is characterized by minimum use of synthetic pesticides and mineral fertilizers in anticipation of protecting natural qualities

(Hansen *et al.*, 2006). However, whether organic systems have overall advantages over conventional agriculture and are likely to achieve sustainable goals is debatable. Organic farming has been claimed as highly context-dependent since there is great uncertainty in its yields and environmental performance (Seufert & Navin, 2017). Particularly, organic and conventional management regimes can both comprise a wide range of farming practices which may affect agricultural performance differently (Gomiero *et al.*, 2011).

In this study, we seek to evaluate the sustainability performance of organic and conventional olive farming under semi-arid climate while taking into consideration of the variation of farming practices applied within the same management system.

Olive is the most essential component of the Mediterranean diet, which has long been proposed as one of the healthiest eating styles (Willett *et al.*, 1995). Studies suggest that the lipid profile as well as the antioxidant and other biological activities of phenolic compounds in olive oil are associated with decreased lipid and DNA damage, and thus have potential cardiovascular and anti-cancer effects (Covas *et al.*, 2009; Gill *et al.*, 2010). However, olive production and the persistence of the Mediterranean diet is currently threatened by the ongoing challenges of global markets, industrial agriculture and climate change (Ponti *et al.*, 2016). Pronounced warming (over 4-5°C), decrease in precipitation (over 25-30%) and more frequent extreme heat events (Giorgi & Lionello, 2008) are likely to reduce multiple cropping suitability, change disease and pest distributions, and exacerbate current water scarcity pressure on olive cultivation in the Mediterranean region. High economic losses from olive culture are likely to happen in Italy, Greece, and the Middle East, especially for small farms in areas prone to desertification (Ponti *et al.*, 2014). To ensure food, nutritional and socio-economic security, it is critical to develop context-specific indicators for agricultural sustainability and identify effective alternatives to sustain olive production and the Mediterranean dietary pattern.

To fulfill these goals, we first developed a framework and relevant indicators for evaluating the sustainability performance of olive farming by reviewing existing sustainability assessment tools and examining the characteristics and challenges of olive cultivation in the Mediterranean region. We then performed a case study in Cyprus to demonstrate the application of these criteria and indicators, and assess the sustainability of organic and conventional olive farming with a special focus on their environmental and human health implications.

This study will serve as a pilot study on sustainable agricultural development in Cyprus, provide empirical experience for rainfed and irrigated olive farming in semi-arid regions, and inspire small farmers in marginal areas to respond actively and effectively to climate change impacts.

2. Selection of Sustainability Indicators

The suitability and outcomes of alternative practices often vary due to multiple factors such as agroecological zones, farm sizes, cultural preferences, economic policies, etc. (Sardinas & Kremen, 2015), highlighting the need for site-specific assessment of implementation and sustainability. In this section, we seek to identify a set of appropriate and credible sustainability indicators for olive farming in the Mediterranean region by reviewing existing assessment methodologies as well as the characteristics and challenges of olive cultivation in this area. The indicators and corresponding measuring methods are expected to be relevant, practical, and useful for communication with stakeholders and decision-makers.

2.1 Existing methodologies for measuring agricultural sustainability

2.1.1 The concept of agricultural sustainability

The idea of sustainable agriculture is not new. In the US, the earliest form of sustainability movement almost occurred synchronously with the industrialization of agriculture (Reganold *et al.*, 1990). In his book *Farmers of Forty Centuries: Organic Farming in China, Korea, and Japan*, originally published in 1911, Franklin King, former official of the U.S. Department of Agriculture, depicted how farmers in the East Asia cultivated their land intensively but sustainably for 4,000 years without depleting the soil fertility (2004). In 1989, the Food and Agriculture Organization (FAO) council, defined sustainable agriculture as:

> *"…the management and conservation of the natural resource base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such development conserves land, water, plant and animal genetic resources, is environmentally non-degrading, technically appropriate economically viable and socially acceptable"* (FAO, 1998).

Although this definition has set the basis for many of the later conversations about sustainable agriculture, the concept of "sustainability" is subject to divergent interpretations. One school of thought has defined sustainable agriculture as an alternative ideology or management approach to conventional agriculture (MacRae *et al.*, 1990), which incorporates key values such as low-input, diversity, harmony with nature, equity, self-sufficiency, into describing sustainable systems. Another widely-supported interpretation of sustainability as a property of agriculture emphasizes the system's ability to fulfil a balanced set of goals including food provision, enhancement of environment, economic viability, and social welfare as well as the ability to maintain through time (Hildebrand, 1990).

Hansen (Hansen,1996) criticized both interpretations for their limited usefulness to guide changes in agriculture. Interpreting agricultural sustainability as an ideological philosophy is subject to a lack of generality, a distorted caricature of conventional agriculture, and circular logic. Interpreting sustainability as a system's property is logically consistent, but requires the characterization of agricultural sustainability to be "literal, system-oriented, quantitative, predictive, stochastic and diagnostic".

In addition, the inherent problems in conventional agriculture, i.e. high input of synthetic chemicals and monoculture, are also extending the social aspects of agricultural sustainability from food provision and self-sufficiency to other dimensions of human health (Horrigon *et al.*, 2002). The increasing antibiotic resistance in humans driven by the extensive use of antibiotics in animal agriculture (Bogaard *et al.*, 2000), the elevated cancer risks and endocrine disruption from pesticide use for farm workers and consumers (Alavanja *et al.*, 2013; Cecchi *et al.*, 2012), and the development of chronic non-communicable diseases from unbalanced diets (Popkin *et al.*, 2006), are emerging topics that need to addressed by sustainable agricultural production.

2.1.2 Approaches to measure sustainability

Measuring and assessing sustainability is challenging. First, the temporal component of sustainability involves future performance and outcomes that are difficult to observe or predict in the given time frame of evaluation (Harrington, 1992). Among the three pillars of sustainability, i.e. environmental, economic and social sustainability, it is relatively easier to quantify current conditions and project future changes of air quality, soil fertility, and other environmental properties, but more difficult to describe and foresee the long-term evolution of social values, relationships, and other economic and social aspects of our production. Second, sustainability is a broad concept which involves multidimensional, complex information. Effective evaluation needs to reduce the complexity of information while retaining the comprehensiveness of the assessment. Third, while assessment tools are often developed by researchers, they should produce useful results that can be translated into meaningful, practical decisions (De Olde *et al.*, 2016).

Generally, there are two main approaches for assessing sustainability. The "bottom-up" approach requires systematic collaboration between researchers and farmers to understand and select a set of key indicators which are interpretable and accessible to the stakeholders (King *et al.*, 2000). In contrast, the "top-down" approach usually starts with a holistic view of sustainability which is then broken down into groups of sub-indicators.

By following and often combining these two approaches, many studies have focused on developing appropriate indicators to analyze and compare the sustainability performance of farms. For example, Indicauters de Durabilité des Exploitations Agricoles (IDEA), an assessment tool widely used in Europe, was developed in six main stages and was based on 41 indicators covering the viability, livability, and environmental reproducibility of farm systems (Candido *et al.*, 2015). Some studies have also proposed structured frameworks to identify principles, criteria and indicators (PC&I) for sustainability assessment. The Sustainability Assessment of Farming and the Environment (SAFE) is a hierarchical framework of which the principles and criteria are derived from the functions of agroecosystems. (Cauwenbergh *et al.*, 2006). The Monitoring Tool for Integrated Farm Sustainability (MOTIFS) (Meul *et al.*, 2008) emphasized stakeholder participation and expert consulting in the four-step methodological process of generating relevant themes and indicators, and allows a mutual comparison of sustainability using radar graphs.

To further simplify the description of farming systems, several composite indicators have been constructed for sustainability evaluation. Depending on the scope and the application of the study, indicators can be aggregated with or without weights. Methods such as principal components analysis (PCA) and factor analysis are often used when assigning weights to different indicators. Composite indices often require sensitivity analysis to test their robustness (Nardo *et al.*, 2005). Examples of composite indices include Response-Inducing Sustainability Evaluation (RISE), where a farm's score for each of the 10 themes (soil use, animal husbandry, nutrient flows, water use, energy and climate, biodiversity, working conditions, quality of life, economic viability, and farm management) is the average of the normalized scores for several subthemes (Hani *et al.*, 2003), and Organic Livestock Proximity Index (OLPI), where indicators are weighted and aggregated into a global index considering both the European Community regulations for organic livestock farming and agroecological principles (Mena *et al.*, 2011).

In 2018, the UN Inter-agency and Expert Group on Sustainable Development Goal Indicators (IAEG-SDG) approved FAO's methodology for SDG indicator 2.4.1 "Proportion of agricultural area under productive and sustainable agriculture" under SDG target 2.4 (FAO, 2018):

"By 2030, ensure sustainable food production systems and implement

resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality."

The SDG indicator 2.4.1 consists of 11 sustainability sub-indicators, and the results are displayed through an indicator dashboard at the national level (Table 1).

Table 1. The 11 sub-indicators of SDG indicator 2.4.1.

Theme	Sub-indicator	Sustainability dimension
Land productivity	Farm output value per hectare	Economic
Profitability	Net farm income	Economic
Resilience	Risk mitigation mechanisms	Economic
Soil health	Prevalence of soil degradation	Environmental
Water use	Variation in water availability	Environmental
Fertilizer pollution risk	Management of fertilizers	Environmental
Pesticide risk	Management of pesticides	Environmental
Biodiversity	Use of biodiversity-supportive practices	Environmental
Decent employment	Wage rate in agriculture	Social
Food security	Food insecurity experience scale (FIES)	Social
Land tenure	Secure tenure rights to land	Social

Note. Adapted from *SDG Indicator 2.4.1. Proportion of Agricultural Area under Productive and Sustainable Agriculture. Methodological Note* (FAO, 2018).

2.2 Characteristics and challenges of olive cultivation

2.2.1 Overview of olive cultivation and production

Olive oil, the major product of olive tree culture, is of great importance to the economics, tradition, and human health in the Mediterranean region (Bach-Faig, *et al.*, 2011; Alonso & Vlad, 2013). Olive is the leading agricultural export of Mediterranean countries including Spain, Italy, Greece, etc., whose olive oil production accounts for more than 90% of the world's total amount (Souilem *et al.*, 2017).

The regular consumption of olive oil is also believed to be partly responsible for the association between the Mediterranean diet and a lower risk of cardiovascular diseases (Estruch *et al.*, 2013). Previous studies indicate that the high levels of monounsaturated fatty acids (e.g. oleic acid) and biologically active phenolic compounds in virgin olive oils may deliver multiple health benefits. For example, oleocanthal (2-(4-Hydroxyphenyl) ethyl (3S,4E)-4-formyl-3-(2-oxoethyl) hex-4-enoate), a phenolic compound of particular interest, is a natural anti-inflammatory and antioxidant chemical which can attenuate the development of numerous chronic diseases (Lucas *et al.*, 2011). The chemical composition and polyphenol content of the olive oil are mainly determined by the extraction process (crushing and malaxation) (Lozano-Sánchez *et al.*, 2009), but may also be affected by the agronomical practices applied during cultivation. Some evidence suggests that organic olive oil has higher concentrations of polyphenols than conventionally produced counterparts (Rosati *et al.*, 2014), but the associated health benefits still needs evaluation.

2.2.2 Sustainability challenges of olive cultivation

The Mediterranean region is a primary climate change hotspot which may have extensive impacts on olive cultivation (Tanasijevic *et al.*, 2014). Although rising temperatures are expected to extend cultivable areas for olive growing northward, the suitability of olive cultivation and hence the yield in the southern part of the Mediterranean basin are likely to decrease (Fraga *et al.*, 2020). The range of olive fruit fly (*Bractocera oleae* (Gmelin.)), the most devastating pest of olives, may also extends northward (Ponti *et al.*, 2013). Climate anomalies such as early spring frosts can also affect olive production since olive is sensitive to long periods of freezing.

Another major challenge posed by climate change is the increased water demand in olive culture. Although olive is highly adaptable to drought and dry spells, it usually has better produce with higher rainfall or irrigation especially in the early growing season (Palese *et al.*, 2010). While net irrigation requirements are projected to increase by 18.5% over the Mediterranean region (Tanasijevic *et al.*, 2014), water availability in the area is likely to reduce (García-Ruiz *et al.*, 2011). Therefore, there is a pressing need for optimizing water usage in oive cultivation while maintaining stable productivity and quality.

In addition to the impacts of climate change, olive cultivation and production is also associated with other environmental problems, including biodiversity loss, land degradation, soil and water contamination from fertilization, use of pesticides, and exhausted pomace (Rey *et al.*, 2019). Olive mill wastes might damage the environment due to their high phytotoxicity, but also represent a precious resource for by-products since they contain most of the phenolic content of the olive fruits.

2.3 Creating site-specific indicators

2.3.1 Limitations of existing indicators

Although various parameters or indices have been developed for measuring agricultural sustainability, we decide to propose a new framework for evaluating the sustainability of olive cultivation. The reasons are as follows.

First, many of the existing methods have too many indicators or components to characterize sustainability, which renders assessment technically difficult and not cost-effective. At the same time, these approaches often fail to account for the interrelations among different components. For example, in the SAFE framework (Cauwenbergh *et al.*, 2006), biodiversity and habitat diversity are treated as two separate criteria despite their correlation.

Second, composite indices also suffer from correlating variables, as well as subjectivity of choosing the weighting system (Gennari *et al.*, 2019). They may lack interpretability and are often unable to reveal the condition or progress of specific components, which makes policy-making difficult.

Third, we believe sustainability indicators should be comprehensive enough to cover the broad scope of the sustainable development goals. However, even the SDG indicator 2.4.1 fails to measure the capacity of the agricultural systems to "adapt to climate change, extreme weather, drought, flooding and other disasters", which is explicitly stated in the SDG target 2.4.

Fourth and most importantly, the indicators should be relevant to the scope of this study, which encompasses the growing conditions for olive trees, the environmental characteristics of semi-arid regions, and the nutritional and cultural value of olive oil. Specifically, we think human health implications are important topics in olive oil cultivation and production, but they are seldom included or emphasized in many of the existing evaluation frameworks.

2.3.2 Sustainability indicators for olive cultivation

Based on the notions of the SDGs, the characteristics and challenges of olive cultivation, and our interviews with the farmers, a multi-criteria framework consisting of ten indicators has been developed for the sustainability assessment of olive farming systems. This framework encompasses three major themes, i.e. economic viability, ecosystem health, and human health, to reflect the economic, environmental, and social components of sustainability in olive cultivation. The relevance and demonstration of these indicators will be detailed in the following sections.

Table 2. The multi-criteria framework and sustainability indicators for the evaluation of sustainability performance of olive farming systems.

Theme	Indicator	Sub-theme	Measuring method
Economic viability	1. Farm output value per hectare	Productivity and yield	Survey/ Interview
	2. Gross and Net farm income	Profitability	Survey/ Interview

Table 2. Continued.

Theme	Indicator	Sub-theme	Measuring method
Ecosystem Health	3. Soil physicochemical properties (physical structure + fertility status)	Soil health	Field sampling and lab analysis
	4. Soil carbon sequestration	Soil health, climate change mitigation	Field sampling
	5. Soil microbial community	Soil health, biodiversity maintenance	Field sampling and lab analysis
	6. Water quality	Water health	Field sampling and lab analysis
	7. Water-use efficiency	Water health, climate change mitigation	Survey/ Interview
	8. Arthropod diversity	Biodiversity maintenance	Field sampling
Human health	9. Pesticide application and residue levels	Farmworker safety, consumer health	Interview and lab analysis
	10. Product nutritional quality	Consumer health	Laboratory analysis

3. Case study in Cyprus

3.1 Material and methods

3.1.1 Study area and sites

To apply the selected indicators to sustainability assessment of olive cultivation, we performed a case study in a semi-arid region south of Morphou on the outskirts of the Troodos mountains (35°5'~35°6'N, 32°52'~33°56'E, Figure 1), a place that receives the least rainfall in Cyprus (~350 mm per year) and will continue to suffer from declining precipitation (Payab & Türker, 2018). According to projection, it is expected that the annual temperature in Cyprus will increase by 1.3-1.9 ◦C for the 2021–2050 simulation, and the dry periods with below 1mm of rainfall will increase by 15 days (Giannakopoulos *et al.*, 2010). The greatest changes are expected to occur in the mountainous area of the island, which includes our study area.

Data have been collected across ten sites in two neighboring villages of Skouriotissa and Petra of the same climatic conditions (five organic farms, four conventional farms, and one orchard unmanaged since 1974). These farms have been managed by local smallholders using different management practices for decades. Since we were only able to obtain cross-sectional data for these ten sites, which might provide limited evidence for certain indicators, such as carbon sequestration rates, we also included five sites in a relatively new organic olive orchard (Atsas farm, 35°04'48"N, 32°55'29"E) with 0-4 years of olive cultivation using the same management practices in our study. Part of the Atsas farm is located in the United Nations Buffer Zone, a demilitarized region established in 1964 to prevent fighting.

Since 2003, farmers get permission to enter this area and cultivate arable lands under an agreement between Greek and Turkish Cypriots (UNSC, 2017).

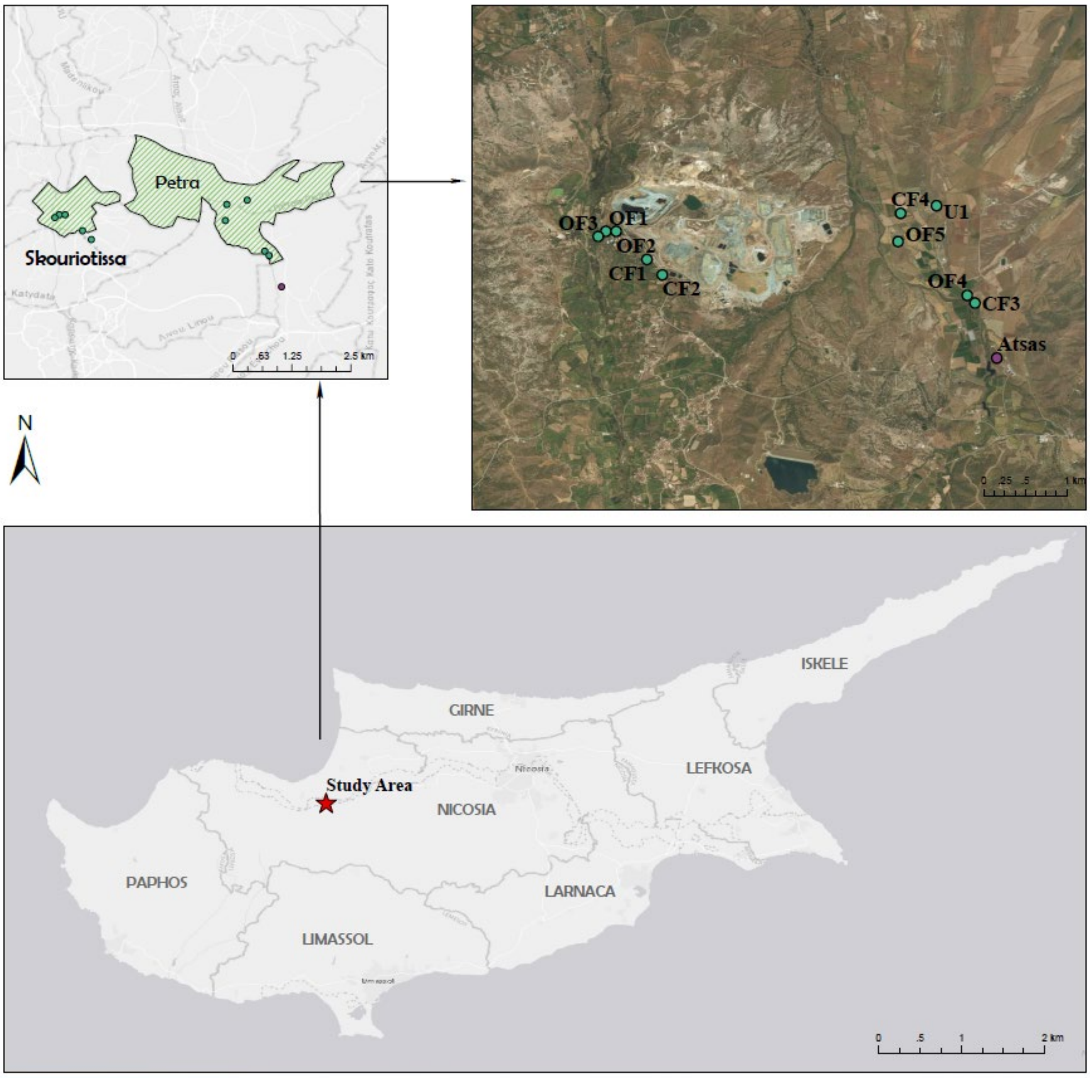

Figure 1. Location of the case study area and sites in Cyprus

3.1.2 Structured farmer survey

Farm owners of each study site were interviewed in August, 2019 using a standardized questionnaire on their farming practices, olive production and oil yield, and target market and gross income (Appendix A). Alternative farming practices considered in this study include: (1) no tillage or reduced tillage; (2) cover cropping; (3) intercropping; (3) organic pest management; (4) organic fertilization; (4) crop–livestock systems (grazing).

3.1.3 Biodiversity survey

To assess the arthropod composition and diversity, which is an important indicator for the influence of farming practices on ecosystem function, a total of 50 pitfall traps and 50 yellow sticky traps were installed on the above-mentioned ten sites on July 2nd, 2019 to monitor the composition and functionality of ground-dwelling (edaphic) arthropods and canopy arthropods (Figure 2). For each farm, five sampling points were located at the vertices and the centroid of a 10m × 10 m quadrat randomly selected inside the orchard to avoid possible edge effects due to neighboring orchards. Pitfall traps with 9 cm height and 7 cm diameter were filled half way with water and laid at soil level. All trapped arthropods were collected after 24 hours, preserved in 70% ethanol and identified to Orders (with Formicidae identified to Family). Sticky traps were 10 × 15 cm two-sided, yellow cards coated with an adhesive and placed on wooden stakes at 1.25 m above the ground. Specimens were collected after 24 hours, labelled, and identified to Orders.

Figure 2. Installation of pit traps (left) and sticky traps (right) for arthropod sampling.

For each site, richness index was calculated based on the number of different orders per trap. Taxa diversity and evenness were obtained following Shannon (H) and Pielou's (J) indices (Magurran, 2004). Given the small sample size and the non-normal distribution of data, the non-parametric test, Mann-Whitney U test (McKnight & Najab, 2010) was performed in R version 3.6.2 to compare the richness, Shannon diversity, and Pielou’s evenness of taxa between organic and conventional farms. Significance was reported at the level of $p < 0.05$.

3.1.4 Soil analysis

Soil samples were collected from the fifteen sites (including five sites at Atsas) in early July, 2019 to test for physicochemical properties. For each of the ten olive orchards, five sub-samples were taken randomly from surface soil of 0-20 cm depth near the major root zone of the olive trees and mixed into one sample. For the five chronological sites on the Atsas farm, five individual samples were collected in a zigzag manner (Estefan & Rashid, 2001) on each site. Soil samples were air-dried, ground and sieved through a 2-mm sieve for subsequent analyses.

Calcium carbonate ($CaCo3$) concentration (%) was determined using a Bernard Calcimeter. Soil pH and electrical conductivity (EC) were determined with 1:2.5 soil to water ratio using the methods described in Soil Survey Staff (Soil Survey Staff, 2014). The soil texture was analyzed using a Bouyoucos hydrometer (Bouyoucos, 1936). Extractable phosphorus (P), and available potassium (K) were measured using Olsen *et al.* (1954), and Hald (1947), respectively.

Total nitrogen (TN) and total organic carbon (TOC) were measured using a CHNS-O analyzer (EuroVector EA3000). $CaCO3$ was removed from the samples by adding HCl before the measurement.

Mann-Whitney U test (McKnight & Najab, 2010) was used to compare soil chemical properties between organic and conventional farms (α=0.05). One-way analysis of variance (ANOVA) was performed in R version 3.6.2 to test if there were any significant differences among the five chronological sites at the Atsas orchard. Tukey's Honestly Significant Difference (HSD) Test was used as the post hoc test to identify the significantly different groups if ANOVA revealed a significant result ($p < 0.05$) (Abdi & Williams, 2010).

3.1.5 Determination of pesticide residues

We selected the following pesticides that are registered and commonly used in olive cultivation for testing: (1) Neonicotinoid pesticides including diflubenzuron, triflumuron, and imidacloprid; (2) Pyrethroid pesticides including α-cypermethrin, λ-cyhalothrin, β-cyfluthrin, and deltamethrin; and (3) Organophosphate including dimethoate, fenthion, and chlorpyrifos. We also included spinosad, glyphosate, and thiacloprid based on the self-reported pesticide use from farmers of our study sites. A complete list of the maximum residue limits (MRLs) for pesticides regulated by the EU can be found at http://ec.europa.eu/food/plant/protection/pesticides/index_en.htm. All stock solutions of the standards (1000 μg/ml) were prepared in acetonitrile (Sigma-Aldrich 34851, Steinheim, Germany) and diluted to the appropriate work concentrations when necessary.

Pesticide residues on olives and in olive oil were determined using the QuEChERS method described in Cunha *et al.* (2007). 100 g olive fruit samples were randomly collected from each site pre- and post- pesticide spraying in early September, 2019. Olive samples were blended and homogenized, and 15g of the homogenized sample was transferred into a 50 ml centrifuge tube. After adding 15 ml of acetonitrile to the sample, the tube was shaken vigorously for 30s and for another 1 min after 6g anhydrous $MgSO_4$ and 1.5g NaCl were added. The tube was then centrifuged at 3000 rpm for 5 min, and 2 ml of the upper phase was transferred into a 15 tube with 300 mg anhydrous $MgSO_4$, 100 mg primary secondary amine (PSA), 100 mg C_{18}, and 15 mg graphitized carbon black. The extract was then mixed and centrifuged at 3000 rpm for 5 min. The organic phase was used for subsequent gas- (GC) and liquid-chromatography (LC) analysis

Olive oil samples from each orchard were collected after the harvest season of 2019 in December. 3 g of the homogenized sample was transferred into a 50 ml centrifuge tube. After adding 10 ml of acetonitrile to the sample, the tube was shaken vigorously by hand for 1 min, and centrifuged at 3000 rpm for 5 min. An aliquot of 4 ml of the acetonitrile extract was transferred into a 15 ml centrifuge tube containing 100 mg PSA (primary secondary amine) and 100 mg C_{18}, and shaken for 30 s and centrifuged at 3000 rpm for 5 min. 1 ml of the cleaned-up extract was then transferred into a screw top tube and acidified by adding 10 μl formic acid solution 5% in acetonitrile. The extract was used directly for GC analysis and diluted with a mobile phase (1:5) for LC analysis.

For less polar, semi-volatile pesticides (i.e. λ-Cyhalothrin, α-cypermethrin, β-cyfluthrin, deltamethrin, chlorpyrifos, glyphosate), we used GC with electron-capture dissociation (ECD) for residue quantification (Agilent 7890A GC, Agilent, US). The other pesticides were analyzed with LC with tandem mass spectrometry (LC-MS-MS). The laboratory measurements of pesticide residues would be compared with self-report pesticide use from farmers.

3.1.6 Oil nutritional analysis

Olives of the same variety harvested from each olive orchard were milled at the Atsas milling system. The olives were crushed and the resulting olive paste was kneaded (malaxation) in a mixer for 30 min at 22°C. The oil was decanted after centrifugation and stored in amber bottles in darkness until analysis.

To prepare for the chemical analysis, 5.0g olive oil of each sample was mixed with 20 mL cyclohexane and 25 mL acetonitrile. The mixture was homogenized and centrifuged at 4000 rpm for 5 min. 25 mL of the acetonitrile phase was collected, mixed with 1.0 mL of a syringaldehyde (4-hydroxy-3,5-dimethoxybenzaldehyde) solution (0.5 mg/mL) in acetonitrile, and evaporated under reduced pressure using a rotary evaporator (Rotavapor R-300, Buchi, Switzerland). The concentrations of phenolic compounds, i.e. hydroxytyrosol, tyrosol, and their derivatives, were measured using quantitative nuclear magnetic resonance (q-NMR) spectroscopy as described in Karkoula *et al.* (2012; 2014). Hydroxytyrosol is mainly present in the form of oleacein (3,4-DHPEA-EDA) and the monoaldehydic form of oleuropein aglycon (3,4-DHPEA-EA), while tyrosol is mainly present in the form of oleocanthal (p-HPEA-EDA) and the monoaldehydic form of ligstroside aglycon (p-HPEA-EA).

3.2 Results

The results for each sustainability indicator are presented below. For this evaluation, we only assessed seven out of the ten indicators. For some of the indicators, including pesticide residue levels and nutritional quality, we may only have partial data given that the laboratory analysis is still being processed. Evaluation of water quality, water use-efficiency, and soil microbial community will be included in future research.

3.2.1 Site characteristics

The locations and summary of farming practices applied on each site are shown in Table 3. A mixture of rain-fed (no-irrigation) and irrigated olive orchards are found in the study region. OF1-3 are no-till, organic farms with permanent ground cover but using different irrigation and grazing strategies. OF4 uses conventional tillage and flood irrigation from March to December. OF5 applies the same irrigation practice but switched from conventional tillage to no-till farming in 2018. All the five organic farms use livestock manure instead of synthetic chemicals for fertilization. CF1 is a no-till, conventional olive orchard using flood irrigation. CF3 implements reduced tillage and uses roundup to remove the weeds. Both CF2 and CF4 are no-till, conventional orchards with no irrigation, and olive trees in CF4 are intercropped with barley (*Hordeum vulgare*).

Table 3. Olive grove data in terms of location, management systems and farming practices.

	ID	Location	Description
	OF1	35°5'34"N, 32°52'58"E	no-till, no irrigation, grazed by donkey, cover crops
	OF2	35°5'34"N, 32°53'2"E	no-till, deficit irrigation, grazed by donkey, cover crops
Organic	OF3	35°5'32"N, 32°52'55"E	no-till, flood irrigation (Feb-May), cover crops
	OF4	35°5'9"N, 32°55'19"E	conventional tillage, no grazing, flood irrigation (Mar-Dec)
	OF5	35°5'30"N, 32°54'52"E	first year no-till, no grazing, flood irrigation (Mar-Dec)
	CF1	35°5'23"N, 32°53'14"E	no-till, flood irrigation
	CF2	35°5'17"N, 32°53'20"E	conventional tillage, no irrigation
Conventional	CF3	35°5'6"N, 32°55'22"E	reduced tillage, roundup, flood irrigation (Mar-Dec)
	CF4	35°5'41"N, 32°54'53"E	conventional tillage, no irrigation, intercropping with barley
Unmanaged	U1	35°5'44"N, 32°55'7"E	unmanaged since 1974

3.2.2 Economic viability

Annual yield and gross income of OF1-5 and CF3-4 are shown in Table 4. Information on management costs and net income is still being collected. OF1-3 have a lower tree density as compared to the other four sites, but the annual fruit and oil yield of OF2 and 3 are comparable to the two conventional orchards with higher tree density. The productivity of OF1, the non-irrigated organic grove, is 20% lower than the two organic sites with deficit irrigation (OF2) and flood irrigation (OF3). The unit price of oil produced by OF1-3 greatly exceeds the average level of the other four sites, which might be due to the high polyphenol content in the oil (see 3.2.4.2). Overall, the organic orchards have a higher gross income per hectare than the conventional ones.

Table 4. Annual olive fruit and oil yield and gross income in the past five years (2014-2018).

Site	Tree density (/ha)	Olive fruit yield (t/ha)		Oil yield (t/ha)		Oil unit price (€/l)		Gross income per hectare (€)	
		Good	Bad	Good	Bad	Good	Bad	Good	Bad
OF1	133.3	3.3	-	0.56 (17.0%)	-	30	-	18,400.9	-
OF2	133.3	4	-	0.67 (16.8%)	-	30	-	22,015.3	-
OF3	133.3	4	-	0.67 (16.8%)	-	30	-	22,015.3	-
OF4	200	5	1.75	0.75 (15.0%)	0.23	4	5	3,285.9	1,259.6
OF5	200	5	1.75	0.75 (15.0%)	0.23	4	5	3,285.9	1,259.6
CF3	200	4	1	0.63 (15.8%)	0.14	3	4	2,070.1	613.4
CF4	200	3	-	0.50 (16.7%)	-	3	-	1,642.9	-

3.2.3 Ecosystem health

3.2.3.1 Soil health and carbon sequestration

(1) Ten sites

Selected physicochemical properties of the ten sites are shown in Table 5. Soil texture is mainly sandy in the study region. All of the ten sites had a soil pH value greater than 7.0 with OF1 and OF2 slightly alkaline (pH: 7.4-7.8) and the others moderately alkaline (pH: 7.9-8.5).

Table 5. Soil physicochemical properties of the ten sites at 0-20 cm.

	OF1	OF2	OF3	OF4	OF5	CF1	CF2	CF3	CF4	U1
% sand	54.2	54.2	54.2	58.2	58.2	50.2	48.2	58.2	42.2	-
% silt	20.0	20.0	20.0	12.0	18.0	22.0	32.0	16.0	20.0	-
% clay	25.8	25.8	25.8	29.8	23.8	27.8	19.8	25.8	37.8	-
$CaCO_3$ (%)	0.6	0	0.6	4.0	3.8	1.0	2.2	3.0	3.8	5.4
EC (mS/cm)	0.37	0.30	0.19	0.23	0.23	0.43	0.23	0.26	0.35	0.17
pH	7.80	7.77	8.20	8.40	8.47	8.16	8.46	8.27	8.12	8.28
Olsen P (ppm)	13.2	8.07	2.64	1.06	2.46	4.24	3.56	0.68	6.17	1.13
K (ppm)	443	575	528	559	401	425	477	376	668	376
TN (%)	0.158	0.138	0.111	0.077	0.074	0.153	0.097	0.088	0.145	0.073
TOC (%)	1.788	1.505	1.039	0.570	0.606	1.538	0.875	0.737	1.167	0.611

For indicators of soil fertility, Olsen P ranged from 0.68 to 13.2. The highest levels of bioavailable phosphorus were found in OF1 and OF2, followed by CF4 and CF1. CF4 also had the highest soil K level among the ten sites, while CF3 was the lowest in both Olsen P and K concentrations. The unmanaged site U1 was relatively low in soil P and K. There were no significant differences in soil fertility (Olsen P: $p = 0.905$; K: $p = 0.730$) between the organic and conventional systems (Table 6).

Table 6. Comparison of Olsen P, K, TN and TOC in organic and conventional olive orchards (Mann-Whitney U test, α=0.05).

	Organic		Conventional		
	Mean (SD)	Median	Mean (SD)	Median	P-value
Olsen P (ppm)	5.48 (5.08)	2.64	3.66 (2.28)	3.90	0.905
K (ppm)	501.2 (75.72)	528	486.5 (127.83)	451	0.730
TN (%)	0.11 (0.04)	0.11	0.12 (0.03)	0.12	0.730
TOC (%)	1.10 (0.54)	1.04	1.08(0.35)	1.02	0.905

With regards to soil nitrogen, OF1, CF1, CF4 and OF2 had the highest levels of TN, whereas only about half of their soil nitrogen content were found in U1, OF5, OF4, and CF3 (Table 5). For soil organic carbon, higher TOC stocks were also observed in OF1, CF1, OF2, and CF4. From Figure 3, there was a significant positive correlation between TN and TOC among all sites ($p < 0.0001$, Adjusted-$R^2 = 0.91$). No difference was observed in soil nitrogen or organic carbon between organic and conventional systems (Table 6).

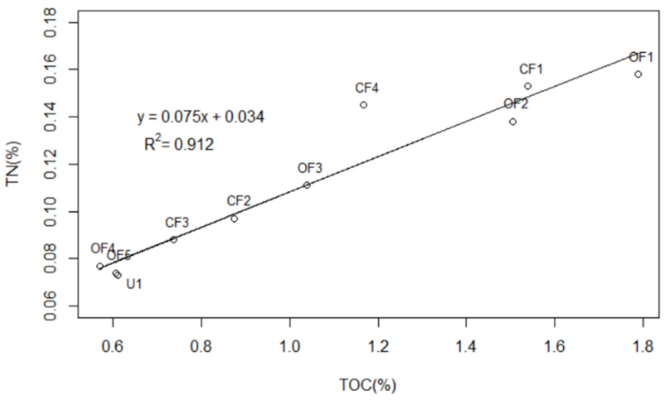

Figure 3. The correlation between total organic carbon (TOC) and total nitrogen (TN) across ten sites.

(2) Atsas farm

For the Atsas farm, the one-way ANOVA and Tukey's HSD test revealed that soil bioavailable P and K were significantly higher (Olsen P: $p = 0.905$; K: $p = 0.730$) in the uncultivated (0 year) field than the fields with olive trees planted on (Figure 4. A, B). There was no significant difference in soil fertility among olive orchards with 1-4 years of cultivation. No significant difference was observed for nitrogen and organic carbon stocks among the fields with 0-4 years of cultivation (Figure 4. C, D).

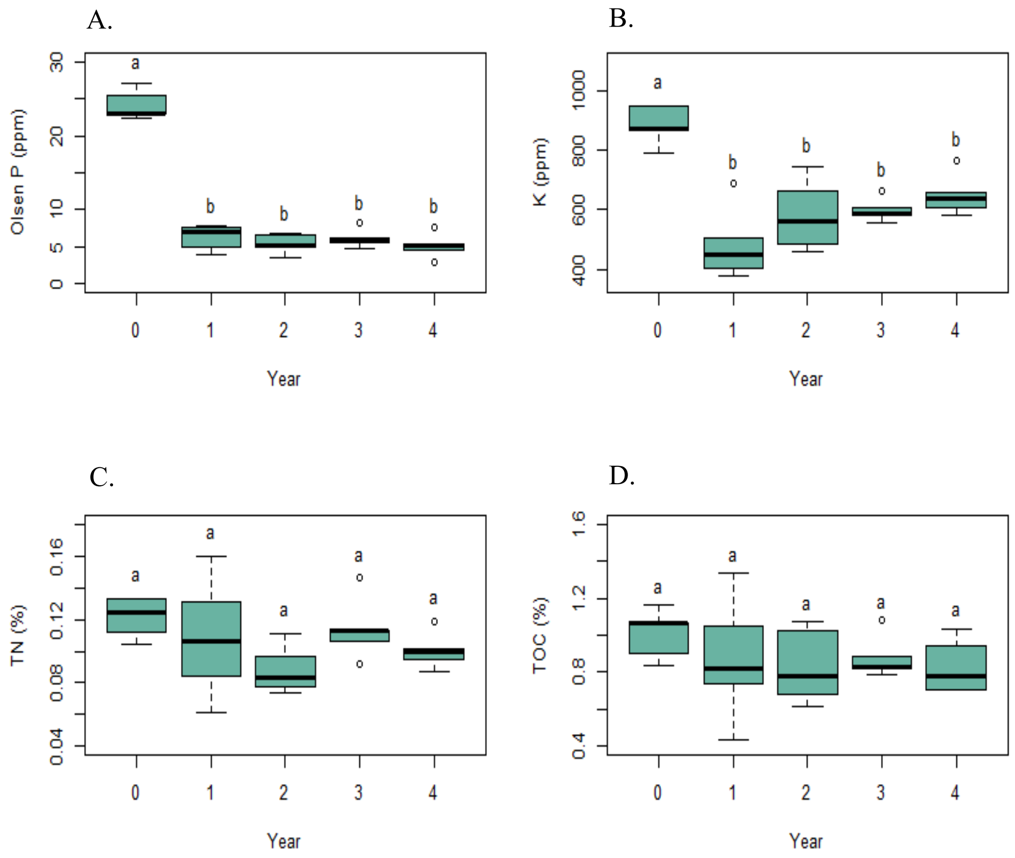

Figure 4. Soil (A) Olsen P, (B) K, (C)TN, and (D)TOC levels of the fields with 0-4 years of olive cultivation at the Atsas farm. Measurements indicated by the same letter within each plot did not differ statistically from each other (Tukey's HSD test, α=0.05).

3.2.3.2 Biodiversity maintenance

(1) Edaphic arthropod abundance and diversity

A total of 621 edaphic arthropods were captured by pitfall traps in the ten olive orchards and were classified into ten different taxa: Isopoda, Opiliones, Araneae, Collembola, Archaeognatha, Orthoptera, Blattodea, Hemiptera, Coleoptera, and Hymenoptera (Formicidae) (Table 7). The pitfall traps also captured 16 individuals belonging to the taxa Diptera and Hymenoptera which are not true ground-dwelling insects and were thus not considered in the analysis.

In total, the most dominant taxa of the soil arthropod community were Formicidae (53.0%), Collembola (27.7%), Coleoptera (8.9%), Araneae (6.9%), and Hemiptera (1.6%). Orthoptera, Isopoda, Archaeognatha, Opiliones, and Blattodea collectively accounted for the remaining 1.9% of the captured edaphic arthropods.

Table 7. Total number of individuals, richness, diversity and evenness of edaphic arthropods community captured in the different olive orchards.

Group	OF1	OF2	OF3	OF4	OF5	CF1	CF2	CF3	CF4	U1
Arachnid										
Isopoda	0	0	0	0	0	0	0	0	3	0
Opiliones	0	0	1	0	0	0	0	0	0	0
Araneae	8	5	9	5	3	2	4	6	0	1
Entognatha										
Collembola	0	11	25	53	59	2	4	15	3	0

Table 7. Continued.

Group	OF1	OF2	OF3	OF4	OF5	CF1	CF2	CF3	CF4	U1
Insecta										
Archaeognatha	0	0	1	0	0	0	0	0	0	0
Orthoptera	0	0	0	1	1	0	0	0	0	0
Blattodea	2	0	1	0	0	0	0	1	1	0
Hemiptera	0	3	3	0	0	2	0	1	0	1
Coleoptera	4	5	7	3	4	3	1	1	24	3
Hymenoptera (Formicidae)	62	46	16	9	42	16	12	44	8	74
Total abundance	76	70	63	71	109	25	21	68	39	79
Richness (R)	4	5	8	5	5	5	4	5	5	4
Shannon diversity index (H)	0.654	1.106	1.579	0.862	1.101	1.437	1.096	1.215	1.112	0.296
Pienou's eveness (J)	0.472	0.687	0.812	0.536	0.614	0.739	0.791	0.624	0.691	0.214

Figure 5. reveals the different composition of edaphic arthropod community of the ten sites. OF4, OF3, OF5, and CF3 had a larger proportion (＞20%) of Collembola, while OF1, OF2, CF1, CF2, CF4 and U1 had relatively low abundance of Collembola (<20%). U1 was disproportionately dominated by ants (Formicidae), while other taxa only accounted for 6.3% of its total abundance. CF4 also had a substantially higher abundance of Coleoptera compared to other sites.

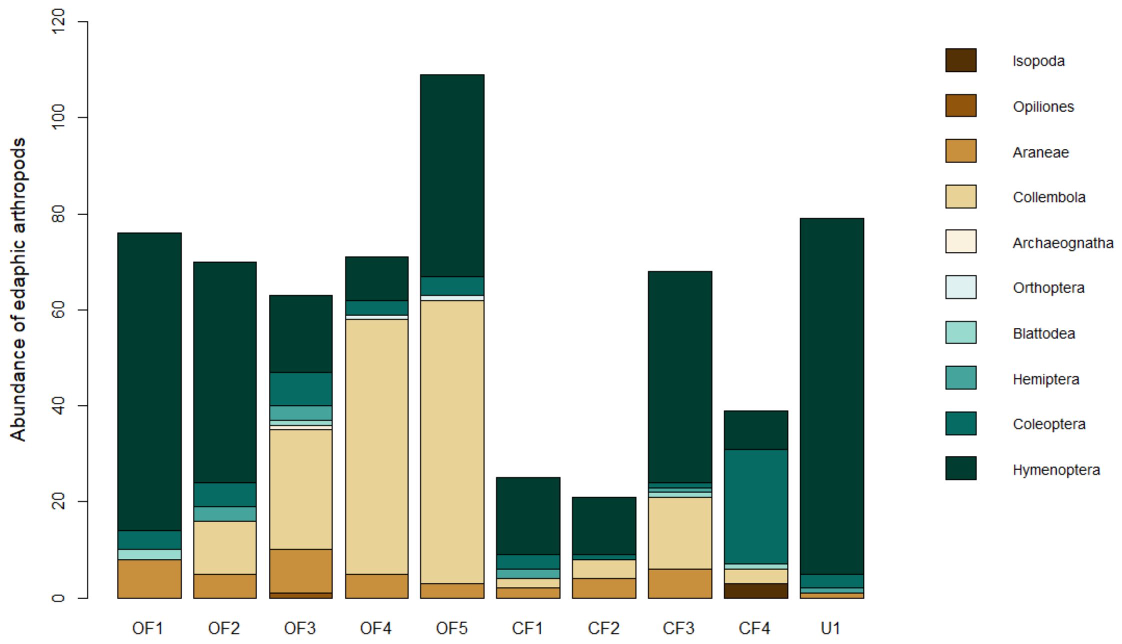

Figure 5. Abundance of edaphic arthropods by taxon captured in the ten olive orchards.

The Mann-Whitney U test revealed a significant difference ($p = 0.032$) in the total abundance of soil arthropods between organic (median: 71) and conventional systems (median: 32) (Table 8). However, no significant differences were observed in the abundance of any of the individual taxon between organic and conventional farms. There were also no significant differences in taxa richness, diversity and evenness between the two groups.

Table 8. Comparison of total abundance, richness, diversity and evenness of edaphic arthropods collected in organic and conventional systems (Mann-Whitney U test, α=0.05).

	Organic		Conventional		
	Mean (SD)	Median	Mean (SD)	Median	P-value
Ant abundance	35.00 (22.00)	42	20.00 (16.33)	14	0.279
Total abundance	77.80 (18.05)	71	38.25 (21.28)	32	0.032 *
Richness (R)	5.40 (1.52)	5	4.75 (0.50)	5	0.661
Shannon diversity (H)	1.03 (0.35)	0.96	1.07 (0.08)	1.10	0.413
Pienou's evenness (J)	0.61 (0.11)	0.60	0.69 (0.08)	0.69	0.286

Note: * indicates the result is statistically significant at the 0.05 level (Mann-Whitney U test)

(2) Canopy arthropod abundance and diversity

The sticky traps captured a total of 5,256 canopy arthropods belonging to 11 different taxa: Araneae, Hemiptera, Diptera, Coleoptera, Hymenoptera, Lepidoptera, Psocoptera, Neuroptera, Ephemeroptera, Thysanoptera, and Orthoptera (Table 9). In total, Thysanoptera was the most abundant order (36.7%), followed by Hemiptera (25.7%), Diptera (21.0%), Coleoptera (10.5%), Hymenoptera (3.6%), and Araneae (1.4%). The remaining 1.1% of the arthropod community was composed of Psocoptera, Lepidoptera, Neuroptera, and Ephemeroptera.

Table 9. Total number of individuals, richness, diversity and evenness of canopy arthropods community captured in the different olive orchards.

Group	OF1	OF2	OF3	OF4	OF5	CF1	CF2	CF3	CF4	U1
Arachnid										
Araneae	9	6	14	5	10	10	7	5	6	0
Insecta										
Hemiptera	156	159	238	244	76	158	97	105	55	63
Diptera	146	185	146	126	61	94	76	124	96	52
Coleoptera	35	43	52	16	21	25	271	40	32	18
Hymenoptera	31	28	34	14	12	13	23	9	15	10
Lepidoptera	3	2	2	1	2	3	2	2	1	2
Psocoptera	3	5	4	1	0	3	6	0	0	4
Neuroptera	0	1	1	3	0	2	0	0	0	0
Ephemeroptera	0	0	1	0	0	0	0	0	0	0
Thysanoptera	653	141	346	124	83	75	34	197	122	155
Orthoptera	0	0	0	1	0	0	0	0	0	0
Total	1036	570	838	535	265	383	516	482	327	304
Richness (R)	8	9	10	10	7	9	8	7	7	7
Shannon diversity index (H)	1.147	1.530	1.454	1.346	1.562	1.521	1.384	1.398	1.487	1.341
Pienou's eveness (J)	0.551	0.696	0.631	0.584	0.802	0.692	0.666	0.718	0.764	0.689

From Figure 6, while 63.0% of the canopy arthropods in OF1 belonged to Thysanoptera, it only accounted for 6.6% of the total individuals captured in CF2. In contrast, CF2 had the highest proportion of Coleoptera (52.5%) among the ten sites.

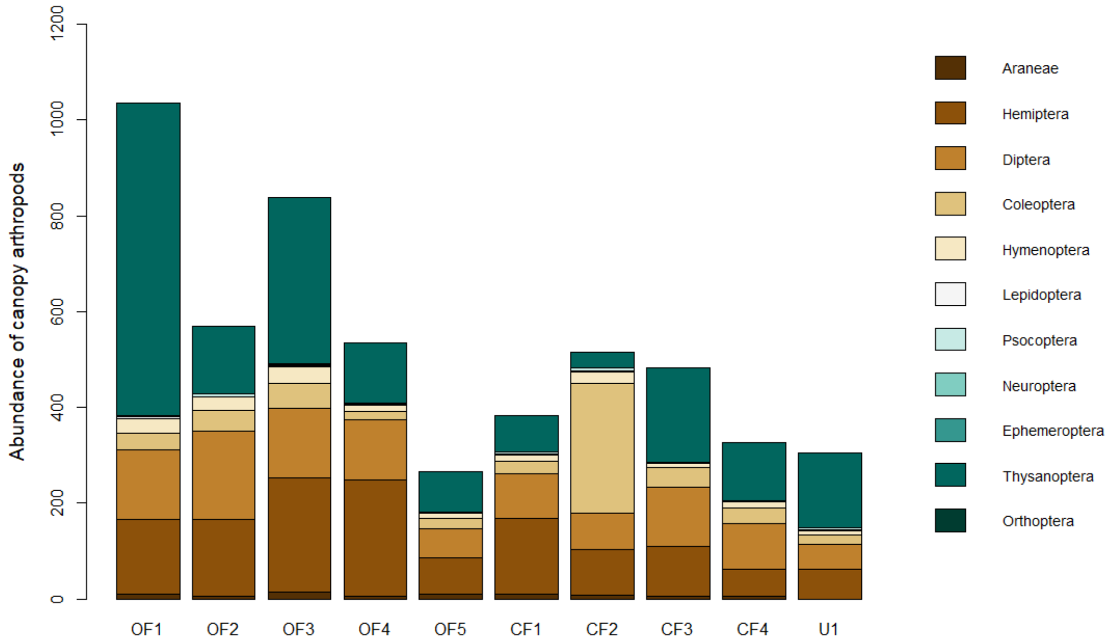

Figure 6. Abundance of canopy arthropods by taxon captured in the ten olive orchards.

The larger standard deviation indicated a greater variation in the total canopy arthropod abundance in the organic systems, but no significant difference ($p = 0.191$) was observed between the organic and traditional sites using the Mann-Whitney U test (Table 10). Similar results were found for taxa richness, diversity and evenness.

Table 10. Comparison of total abundance, richness, diversity and evenness of canopy arthropods collected in organic and conventional systems (Mann-Whitney U test, α=0.05).

	Organic		Conventional		
	Mean (SD)	Median	Mean (SD)	Median	P-value
Total abundance	648.80 (296.72)	570	427.00 (87.33)	432.5	0.191
Richness (R)	8.80 (1.30)	9	7.75 (0.96)	7.5	0.256
Shannon diversity (H)	1.41 (0.17)	1.45	1.45 (0.07)	1.44	1.000
Pienou's evenness (J)	0.65 (0.10)	0.63	0.71 (0.04)	0.71	0.413

3.2.4 Human health

3.2.4.1 Pesticide application and residue levels

Since lab analysis of pesticide residues is still underway, in this report we will only assess and compare the qualitative data of pesticide application reported by the farmers (Table 11). Survey results on pesticide application were not available for CF1 and CF2.

OF1, OF2, and OF3 reported no pesticide application in olive cultivation. Instead, these three organic farms adopted several other pest management practices including selecting and growing hedgerows and companion plants (*Dittrichia viscosa* (L.) Greuter) and placing pheromone traps to repel or attract pest species. The other two organic farms, OF4 and OF5, used Spinosad, a natural insecticide produced by the soil bacterium *Saccharopolyspora spinosa*. Glyphosate-based herbicide and the neonicotinoid insecticide thiacloprid were used in CF3. The owner of CF4 acknowledged the usage of chemical pesticides but refused to report the specific types of the pesticides applied to the orchard.

Table 11. Self-report pesticide application in different olive orchards.

	Pesticide application	Brand Name	Active ingredients	Pesticide class	Other pest management practices
OF1	×	-	-	-	Selecting companion plants Pheromone traps
OF2	×	-	-	-	Selecting companion plants Pheromone traps
OF3	×	-	-	-	Selecting companion plants Pheromone traps
OF4	√	Success Tracer	Spinosad	Spinosyn	×
OF5	√	Success Tracer	Spinosad	Spinosyn	×
CF3	√	Roundup Thiacloprid	Glyphosate Thiacloprid	Organophosphorus Neonicotinoid	×
CF4	√	Refuse to report	-	-	×

3.2.4.2 Oil nutritional quality

Table 12 shows the concentrations of phenolic compounds, i.e. hydroxytyrosol, tyrosol, and their derivatives extracted from the dominant olive cultivar in Cyprus, Koroneiki, cultivated on OF1, OF2, CF3, and CF4. Chemical analysis results of the other six sites are underway. Higher concentrations of oleocanthal and oleacein as well as total polyphenols were found in the organic orchards OF1 and OF2.

Table 12. Concentrations of phenolic compounds (hydroxytyrosol, tyrosol, and their derivatives) of organic and conventional olive oil made from Koroneiki olives.

Concentration (mg/kg)	OF1	OF2	CF3	CF4
Oleocanthal	1554	1196	58	142
Oleacein	404	156	35	141
Oleacanthal+Oleacein	1958	1352	92	282
Ligstroside-aglycone (Monaldehyde)	218	216	21	86
Ligstroside-aglycone (Dialdehyde)	379	311	46	477
Oleuropein-aglycone (Monaldehyde)	100	68	24	182
Oleuropein-aglycone (Dialdehyde)	104	14	36	62
Total tyrosol derivatives	2151	1724	124	704
Total hydroxytyrosol derivatives	608	238	95	785
Total polyphenols	**2759**	**1962**	**219**	**1490**

3.3 Discussion

A total of seven indicators covering all three themes of our multi-criteria framework for sustainable olive cultivation have been assessed in our case study in Cyprus. In brief, organic olive orchards display greater benefits for economic viability, soil biodiversity maintenance, and positive human health implications, but substantial variability exists within the same management regime using different farming practices. The significance of these indicators as well as the potential explanations for the observed differences will be detailed in this section.

3.3.1 Economic Viability

Organic farming has long been criticized by its opponents for being less productive and requiring more land to grow sufficient food than conventional systems. According to a previous meta-analysis, a ~20% yield gap has been found between organic and conventional systems, but variation is substantial (Ponti *et al.*, 2011). In this study, the olive fruit and oil yield of organic orchards are comparable to or even slightly higher than those of conventional groves. Given the lower yield of OF1 (~20% lower than OF2-3) and CF4 (lowest among the four sites with 200 trees/ha), irrigation seems to have played a more important role than tree density in determining productivity. One thing to note is that the tree density in both organic and conventional systems in this study is quite low as compared to high-density or super high-density olive orchards (>780 trees/ha) (Díez *et al.*, 2016), which might be due to the physical constraints (e.g. water stress) in the study region and might have thus rendered the yield difference less evident.

For annual gross income, we observe a substantial difference between OF1-3 and the other four sites, mainly attributable to the certified high polyphenol content in the oil produced by OF1-3. Given the fact that we are still collecting the exact management and operational costs of each site, more information is needed to assess the profitability and the overall economic viability of different management systems, but it is very likely that organic olive growing would allow a higher cost/benefit ratio given the higher market price as well as the greater technical efficiency which has been shown in previous studies (Tzouvelekas, *et al.*, 2001).

3.3.2 Ecosystem health

3.3.2.1 Soil Health

(1) Soil fertility

Soil fertility is the ability of soil to sustain agricultural plant growth and stable productivity (FAO, 2015). It has also been suggested as an ecosystem concept which integrates diverse soil functions including nutrient supply (Swift 2000). All crops require a sufficient and balanced supply of plant nutrients from soil. Among these nutrients, nitrogen, phosphorus and potassium are of major importance.

P is the second most limiting element in crop growth on a global scale (Li *et al.*, 2016). Although P is abundant in soil, it can precipitate with Ca when the soil is alkaline, and with Fe and Al when the soil is acidic (Lindsay *et al.*, 1989). Thus, bioavailable P is often lacking, causing a main constraint on agricultural productivity (Dhilon *et al.*, 2017).

Particularly, the bioavailability of phosphorus is related to the sustainability of olive cultivation in two aspects. First, phosphorus nutritional level is positively associated with various productivity parameters of olives, including rate of reproductive bud break, fruitlet persistence, fruit set, total number of fruits, etc. (Erel *et al.*, 2016). Therefore, soil available P is expected to have a direct influence on olive reproductive processes and consequentially production quantity. Second, although P application is very common in olive cultivation in the Mediterranean region, olive trees tend to store soil P when available instead of responding to applied P (Ferreira *et al.*, 2018). Meanwhile, it is estimated that the phosphate rocks, the raw materials for P fertilizers, will be depleted within the next 50 to 100 years if consumed at the current rates (Hawkesford *et al.*, 2012). In addition, the excessive use of P in agriculture can lead to various environmental problems, such as the eutrophication of groundwater (Dodd & Sharpley, 2016). Adequate bioavailability of phosphorus should reduce the usage of P fertilizers and subsequent environmental problems.

For soil K, though K has been found to influence flowering intensity in olive trees (Erel *et al.*, 2008), studies have also shown that olive trees are less likely to be K deficient, and marginal lands in the Mediterranean region are less K poor than expected for olive tree growth (Mouas-Bourbia *et al.*, 2013).

In our study, soil extractable P levels ranged from 0.68 to 13.2 ppm, with most sites below the optimal level of 8 ppm as suggested in Gargouri (2002) for rainfed olive cultivation. OF1 and OF2 had the highest Olsen P levels, followed by CF4 and CF1. CF3 and OF4 had soil P levels lower than the unmanaged orchard. The K levels were less varied among the ten sites. All orchards had an exchangeable soil K level higher or equal to the unmanaged grove as well as the suggested level of 80 ppm, with CF4 the highest and CF3 the lowest. In this respect, soil P management seems to be more essential than soil K to sustainable olive cultivation in the study region.

Several reasons might explain the observed variations in soil fertility among the sites. First, lower tree density, livestock manure application (Fayed, 2010), and permanent ground covers (Pardini *et al.*, 2002) are possible mechanisms to reduce nutrient depletion and maintain high soil fertility in OF1-3. However, flood irrigation may have led to nutrient leaching and thus lower soil available P in OF3. In CF4, intercropping is likely to increase annual ground cover and crop residues in the olive orchard, which may have resulted in higher soil fertility (Bouhafa *et al.*, 2015). However, how resources are allocated as well as the specific effects on soil parameters have not been studied in olive-barley intercropping systems. CF3 has the lowest soil fertility parameters, which might be partly due to the intensive removal of herbaceous species by glyphosate application and tillage as practiced in the orchard. Similar results were found in Ferreira *et al.*, (2013) that the glyphosate and tillage treatments led to lowest pools of soil nitrogen, organic carbon and available P.

(2) Soil nitrogen and organic carbon

Soil nitrogen and soil organic carbon are also important determinants of soil fertility. Besides, soil organic carbon possesses other important functions such as water retention, and is believed to have a high climate change mitigation potential

(Sommer & Bossio, 2014).

In our study, we observed a positive correlation between soil nitrogen and soil organic carbon. Nitrogen retention in soil is likely to be facilitated by an active soil microbial community and abundant organic substrate (Barret and Burke, 2000).

Although we did not observe a significant difference in TN and TOC between organic and conventional farms, olive orchards (OF1, CF1, OF2, OF3) that applied no-tillage practices tended to have higher TN and TOC levels than those using or have used (OF5) conventional or reduced tillage, except for CF4. Again, intercropping seems to have improved overall soil chemical properties in CF4.

Therefore, practices that promote ground cover and residues, such as no-tillage, no herbicide application, cover cropping, and intercropping, rather than organic management itself, are likely to be most protective of soil fertility and bring about mitigation co-benefits.

3.3.2.2 Carbon sequestration

To further evaluate the impact of organic management on carbon sequestration, we compared the five sites with 0-4 years of cultivation on the Atsas organic farm. However, we did not observe any significant differences among these sites.

Whether organic agriculture has a beneficial effect on soil organic carbon is a long-debated topic. Leifeld and Fuhrer (2000) argued that the reported advantages of organic management for SOC in field experiments are largely due to higher application of organic fertilizer compared to conventional farming. Metaregression models in Gattinger *et al.* (2012), however, showed that the mean difference in SOC stocks between organic and conventional systems was still significant even the analysis was restricted to zero net input in organic systems

Given our results are cross-sectional and the years of management are relatively short, long-term monitoring is needed to shed more light on the carbon sequestration potential of organic olive cultivation. Also, we only collected soil samples at a depth of 0-20 cm, which might have failed to reflect the possible changes in the stratification of soil organic matter.

3.3.2.3 Biodiversity maintenance

Although the exact shapes of the biodiversity–ecosystem services relationships are still under debate (Duncan *et al.*, 2015), a large body of literature indicate that biodiversity loss will negatively impact ecosystem functions and services (Haines-Young & Potschin-Young, 2010). In agricultural systems, biodiversity has complex interactions with agricultural management and production (Swift & Anderson, 1994). For example, soil biodiversity is associated with soil health and important soil ecosystem functioning. The presence of diverse soil microbiota and soil fauna including Protoctista, Nematodes and Enchytraeidae, and Collembola and ants, have been reported to improve crop production through various mechanisms such as positive effects on soil physical structure, enhanced interaction between microorganisms and root exudates, greater protection against pests and diseases, etc. (Lavelle *et al.*, 2006). However, the current intensification of olive cultivation in the

Mediterranean region has led to the degradation of fauna and flora diversity in olive orchards (Allen *et al.*, 2006), highlighting the necessity of monitoring and preserving agrobiodiversity to maintain biodiversity-linked agroecosystem services and achieve sustainability of production.

Given budgetary constraints, we were unable to characterize the soil microbiota of our study sites since it required gene sequencing. However, we were able to monitor soil arthropods and canopy arthropods using pitfall and sticky traps, which were simple, economic and could be easily deployed by farmers in their own fields.

As mentioned earlier, soil arthropod biodiversity is linked to important ecological functions such as decomposition of organic matter and biological control of olive pests. Among the edaphic arthropods, ants are the most prominent indicators of agroecosystems conditions and are easy to monitor (Peck *et al.*, 1998). Ants have also been found to be the major predators of the olive fruit fly and olive moth *Prays oleae*, followed by Heteroptera and Coleoptera. (Morris *et al.*, 1999)

Our results added to the evidence that agricultural management practices can affect the composition and diversity of soil arthropod community (Diekotter *et al.*, 2010). First, although we were unable to perform statistical tests of the arthropod diversity of the ten sites, we could still observe some clear distinctions from their abundance profiles as shown in Table and Fig. In our study, U1 was disproportionately dominated by ants (Formicidae), which was consistent with previous research that ants tend to dominate soil arthropod communities in less disturbed orchards (Morris & Campos, 1999). There was also some evidence indicating that tillage could affect ant communities since OF4 (tilled) had a disproportionately low ant abundance as compared to other organically managed olive orchards. Similar results were found in the vineyards (Sharley *et al.*, 2008) that the abundance of several genera of Formicidae was reduced by tillage. Tillage may affect ground-dwelling invertebrates by influencing the litter layer, microclimate, and other habitat characteristics. This effect of tillage was less clear in conventional orchards since the ant abundance and diversity might also be affected by application of different pesticides (Sonoda *et al.*, 2011). For Collembola, another important order involved in the decomposition of soil organic matter, olive orchards that had a higher abundance and proportion of Collembola (i.e. OF4, OF3, OF5, and CF3) were those that had flood irrigation either during the early growing periods or throughout the growing season. This could partly be explained by the fact that Collembola tend to inhabit damper environments (Verhoef & Selm, 1983). Tillage conditions do not seem to have much influence on Collembola abundance although it has been reported to affect collembolan abundances and assemblage structures in other studies (Brennan *et al.*, 2005). The intercropping system CF4, also appeared to have a quite different soil arthropod community profile that it had a higher abundance of Coleoptera. Intercropping may modify arthropod community by providing different habitats and predator-prey dynamics (Song *et al.*, 2010). However, no previous research has looked into the effects of intercropping on arthropod communities in olive orchards. A possible explanation for the high abundance of Coleoptera in CF4 might be the existence of ground beetles (Carabidae) in the intercropped barley as predators of cereal aphids (Scheller, 1984).

Second, organic systems had a significantly higher total abundance of soil arthropods than conventional orchards, although no significance was found in the abundance of any of the individual taxa or the taxa richness, Shannon diversity, or evenness between the two groups. This is consistent with previous research in Greece that higher number of total catches of soil arthropods appeared in the organic olive orchards, but no constant pattern or significant differences in diversity was observed between management systems (Gkisakis *et al.*, 2014). These results to some degree imply the potential adverse effects of pesticide application and intensive management on soil arthropod community in conventional olive orchards, but larger sample size and more specific measurements of potential explanatory variables (e.g. pesticide type and frequency) are needed to investigate the variability within organic and conventional systems.

The canopy of olive trees also hosts important pest control agents such as predators and parasitoids (Ruano *et al.*, 2004). In our study, we observed a greater variability in canopy arthropods composition in the organic systems as compared to soil arthropods as well as to conventional systems. However, the Mann- Whitney U test revealed no significant differences in total abundance, taxa richness, diversity, and evenness between the organic and conventional sites. Similar results were reported by Gkisakis *et al.*(2018) that no significant differences in canopy arthropods diversity were found between organic and conventional systems, due to high variability of farming practices within the same management system.

Again, there are several important factors that have limited our ability to conduct further analysis on biodiversity maintenance. First, with the small sample size (n=10), it was inappropriate to conduct multivariate analysis to evaluate the effect of each individual farming practice on taxa abundance or diversity. Second, due to technical limitations, we were only able to identify the arthropods to the level of order, which made it difficult to decompose the arthropod communities into functional groups, although the functional group approach might be a meaningful, complementary biodiversity measure (Mouchet *et al.*, 2010). Third, we have neglected some important explanatory variables in our investigation. For example, we assumed similar climate conditions among the ten sites given the same sampling date as well as their proximity to each other. However, the microclimate of arthropod habitats within each olive orchard might differ substantially due to different farming practices, canopy cover, ground cover, landscape heterogeneity, etc. Gkisakis *et al.* (2018) found that in addition to farming practices, abiotic factors like temperature, humidity, and landscape were all significant predictors shaping the canopy arthropod community in olive orchards. Fourth, our field sampling was conducted in early July, which failed to include seasonal changes of arthropod communities in our analysis.

3.3.3 Human health

3.3.3.1 Pesticide application and residue levels

The restricted use of synthetic chemicals including pesticides is the most important distinction between organic and nonorganic production systems. While conventional agriculture relies heavily on synthetic pesticides to control pest organisms, only certain chemicals, such as copper sulfate (fungicide), potassium bicarbonate (fungicide), and naturally derived pyrethrin (insecticide), are approved by the European Commission of the European Union (EU) for plant protection in organic agriculture after an extensive evaluation including a range of toxicological tests in animals (EU, 2008). In addition to direct application of active substances, organic production systems also adopt indirect prevention means such as rotation, intercropping, choices of resistant varieties, and biological control, to alter the temporal and spatial dynamics of pest populations (Wyss *et al.*, 2005). In their field enclosure experiments, Crowder *et al.* (2010) suggested that, organic farms exerted the strongest pest control by promoting even communities of natural enemy groups (e.g. predators and pathogens).

In our study, organic sites OF1, OF2, OF3 used companion plants *Dittrichia viscosa* (L.) Greuter (Asteraceae) and pheromone traps to control pest populations in the orchard. *D. viscosa* is a widely adaptive perennial species in the Mediterranean region (Parolin *et al.*, 2014). It has been increasingly employed in the Mediterranean agroecosystems since it hosts efficient predators such as species in the *Macrolophus* genus and beneficial insects which can control the olive fruit fly (Ingegno *et al.*, 2011). Pheromone traps use sex pheromones or aggregating pheromones to lure insects. While the effectiveness of both methods remains to be examined, they are unlikely to cause adverse health impacts on both farm workers and consumers.

The other two organic farms, OF4 and OF5, used spinosad, a mixture of chemical compounds in the spinosyn family derived by fermentation from the soil bacterium *Saccharopolyspora spinosa*. Spinosad is considered a natural product and is approved in organic agriculture by numerous countries (Hertlein *et al.*, 2011). The spinosoid insecticides act on the insect nervous systems by primarily targeting binding sites on nicotinic acetylcholine receptors (nAChRs) with a secondary effect on γ-aminobutyric acid (GABA) receptors (Scott, 2008). This novel mode of action is distinct from other insecticides, and spinosad has not so far shown to cause any cross-resistance (Sparks *et al.*, 2001).

Spinosad has been suggested as a high-efficacy, broad- spectrum pesticide with low ecotoxicity and mammalian toxicity. Although pest predators and parasitoids generally suffer insignificant sub-lethal effects following spinosad application, all previous studies agree that spinosad degrades rapidly (3-7 days) in the field and regard it as one of the most judicious insecticide (Williams *et al.*, 2001).

With regards to human health, no evidence suggests that spinosad is a cancer-causing agent. even when tested in laboratory animals at very high doses (Bunch *et al.*, 2014). For non-cancer effects, only lower body weights and effects to some organs were observed at the highest doses (0.1% spinosad for 1 year) in rats (Yano *et al.*, 2002). In pregnant rats, abnormal vaginal bleeding and increased risks of dystocia and abortions were also observed at the highest doses tested (100mg/kg/day) (Hanley *et al.*, 2002). No treatment-related effects occurred in their offspring.

Given the low human toxicity of spinosad as well as a MRL of 0.02 mg/kg (EU Pesticides database), it is unlikely that individuals would be exposed to high levels of spinosad comparable to those in the animal tests. At the same time, spinosad is absorbed poorly through dermal contact. Therefore, we suggest the application of spinosad in olive cultivation has negligible impacts on farm workers' and consumers' health.

In the conventional farm CF3, two types of pesticides were applied to the olive orchard. Thiacloprid is an insecticide of the neonicotinoid class which acts on the nicotinic acetylcholine receptors of the insects, primarily aphids and whiteflies, and disrupt their nervous system (Tomizawa & Casida, 2000).

The impacts of thiacloprid on bees have been widely debated in the last few years. A large number of studies show that chronic exposure of honey bees (*Apis mellifera* carnica) to thiacloprid in the field at a sublethal concentration can impair various functions including foraging behavior, homing success, navigation performance, social interactions, etc. (Tison *et al.*, 2016; Forfert & Moritz, 2017). In January 2020, the European Commission (EC) decided not to renew approval of Thiacloprid for outdoor use.

Although neonicotinoids are considered less toxic to humans as compared to older insecticides such as organophosphates, emerging evidence indicates that neonicotinoids may also cause severe neurological and developmental toxicity in humans (Cimino *et al.*, 2017). Chronic neonic exposure has been found to be associated with elevated risks of memory loss and finger tremor (Marfo *et al., 2015*), tetralogy of Fallot (Carmichael *et al.*, 2014), and anencephaly (Yang *et al.*, 2014). As in the case of thiacloprid, thiacloprid is classified and labeled as carcinogen category

2 (suspected of causing cancer) and toxic for reproduction category 1B by the European Food Safety Authority (EFSA) based on animal studies (EFSA, 2019). Neoplasia occurred in both rats (2.5 mg/kg/ day for 2 years) and mice (11 mg/kg/day for 18 months) although the mode of action of tumor formation is not entirely clear. Acute human thiacloprid poisoning and death was also reported from deliberate ingestion in a 23-year-old man (Vinod *et al.*, 2014).

However, given the rapid degradation and generally low residue levels of thiacloprid in diet, EFSA suggests that the intended uses of thiacloprid on olive are unlikely to cause health relevant outcomes (EFSA, 2009). No exposure assessment and epidemiological studies have been conducted on the impacts of thiacloprid on farm workers.

In addition to thiacloprid, glyphosate was also applied in CF3 for weeding. Although limited evidence indicates that glyphosate causes cancer in human, there is sufficient evidence for the carcinogenicity of glyphosate in experimental animals (IARC, 2015). The cytotoxicity and genotoxicity of glyphosate has been further proven in a series of studies carried out in exposed humans, in human cells *in vitro*, and in other mammals both *in vivo* and *in vitro*. Glyphosate can induce DNA strand breaks in various cell types, and its metabolite, AMPA, can produce chromosomal aberrations in human lymphocytes (Manãs *et al.*, 2009; Carlos *et al.*, 2014).

For epidemiological studies, Paz-y-Miño *et al.* (2011) found that individuals exposed to the glyphosate sprayed on the border between Ecuador and Colombia showed significantly higher DNA migration levels than the controls. Previous studies have also associated glyphosate with several cancers, including Non-Hodgkin's lymphoma and breast cancer. Thongprakaisang *et al.* (2013) showed that glyphosate could exert proliferative effects on hormone-dependent growth of human breast cancer cell T47D at low concentrations of 10^{-12} to 10^{-6}M via estrogen receptors. There was also an additive estrogenic effect between glyphosate and genistein, a phytoestrogen in soybeans.

Given the reduced pesticide use intensity and lower pesticide toxicity, the organic orchards OF1-5 seem to be more protective of human health as compared to the conventional groves. However, even with the measurements of pesticide residue levels on olive fruit and in olive oil, it is difficult to assess the risk for farm workers and consumers posed by the pesticide application in olive cultivation.

First, it is possible that organic farmers and rural populations are exposed to synthetic pesticides through other pathways such as spray drift from neighboring fields. Unapproved pesticides may also contaminate organic produce through spray drift, fraudulent use, and contamination during transport, storage, packaging, etc. (Mie *et al.*, 2017).

Second, the exposure levels of farm workers and their health relevance in different farming systems are still arbitrary. Very few studies have assessed and compared pesticide exposure of organic and conventional farmers. To the best of our knowledge, only one published study conducted in Portugal has compared pesticide exposure in organic and conventional agricultural workers (Costa *et al.*, 2014). The results showed significantly lower concentrations of urinary organophosphates and carbamates in organic farmers than in conventional farmers, and confirmed the increased presence of DNA damage in farmers exposed to pesticides. No significant differences in urinary pyrethroids or thioethers concentrations or any explicit health outcomes have been found.

Third, no information is available for the consumers' daily intake levels of the olive oils produced by the orchards in our study. There is also little evidence for the long-term health effects of low-level dietary exposure to different pesticides.

3.3.3.2 Oil nutritional quality

Perceived nutritional benefits are one of the primary reasons for organic consumers to pay generally higher prices for food products (Williams 2007). However, existing systematic reviews and meta-analysis have presented mixed results that are largely inconsistent with these perceptions. Growth chamber studies (Mengel *et al.*, 1981) and controlled field experiments provide evidence that some management practices such as fertilization and crop rotation can exert influence on crop development and nutritional quality. (Wang *et al.*, 2007). For other agronomic measures such as pesticide use, little is known about their effects on crop nutrition (Brandt *et al.*, 2001). In the meantime, crop nutrient composition is also greatly affected by environmental factors such as soil conditions, growing seasons, weather and climatic variables, crop cultivars, postharvest storage, etc. (Hornick *et al.*, 1992). Therefore, whether organic produce contain higher or lower levels of certain nutrients than conventional ones varies depending on the specific nutrients, crop species and cultivars, and other environmental conditions. In addition, how these nutritional differences between organic and conventional foods are relevant for human health is inadequately explored.

In our study, the organic farms OF1 and OF2 had higher concentrations of oleocanthal and oleacein as well as total polyphenols than the conventional farms CF3 and CF4. Polyphenols are "plant secondary metabolites derived exclusively from the shikimate derived phenylpropanoid and/or the polyketide pathway(s), featuring more than one phenolic ring and being devoid of any nitrogen-based functional group in their most basic structural expression" (Quideau *et al.*, 2011). According to the carbon/nitrogen (C/N) balance theory, the plant will first manufacture compounds such as proteins and secondary metabolites including alkaloids, glucosinolates, and non-protein amino acids which contain high nitrogen content. When available nitrogen is a limiting factor, carbon-containing compounds such as starch and cellulose, as well as non-nitrogen-containing secondary metabolites including phenolic compounds will be prioritized (Haukioja *et al.*, 1998).

In organic agriculture, the use of external inputs including mineral nitrogen (N) fertilizers is restricted. The maximum annual manure application rate regulated by EU is 170 kg N per hectare (EU, 2007). In contrast, there is no limit on N input in conventional agricultural systems, and mineral fertilizers such as ammonium nitrate and urea are dominant in nitrogen fertilization.

Therefore, the higher concentrations of polyphenols in OF1 and OF2 might be partly due to the low input of nitrogen in organic systems, as opposed to the regular application of synthetic fertilizers in CF3 and CF4. Significantly higher amounts of phenolic compounds have also been found across a variety of organically grown crop species such as grapes, pecan, etc. (Mulero *et al.* 2010; Malik *et al.* 2009; López-Yerena *et al.* 2019). A decline in hydroxytyrosol concentration in EVOO was also reported when olive trees were applied with N, P, K fertilizers (Dabbaghi *et al.* 2019). Another possible explanation for the higher polyphenol concentrations in OF1 and OF2 might be the lower tree density which could have affected olive growth cycle and led to increased polyphenol levels (Garrido *et al.* 2016). However, the effect of tree density on phenolic compounds in olives requires further research.

When comparing OF1 and OF2, between which the only difference was the irrigation status, higher concentrations of phenolic compounds were detected in the olive oil from OF1 (no irrigation). Water stress has been reported to affect the physiological parameters of olive trees and induce the accumulation of phenolic compounds as antioxidants in olive fruit and leaf, especially oleuropein (Petridis *et al.* 2012). Meanwhile, the severity of water stress may exceed the tolerant capacity of olive trees and lead to increased oxidative stress and adverse effects on oil quality. In our study region, no irrigation did not seem to have a negative impact on polyphenol concentration. In addition, Artajo *et al.* (2006) indicates that in the samples from the non-irrigated trees, a higher proportion of the polyphenols were partitioned into the pomace. In contrast, in the samples from the irrigated trees, most of the phenolic compounds were partitioned into in the wastewater. Therefore, optimal water stress conditions not only increase phenolic compounds during the tree development, but also increase the phenolic content during the extraction process.

With regards to human health, clinical and epidemiological data have provided support to the potent antioxidant and anti-inflammatory properties of polyphenols present in virgin olive oil. Oleuropein is the most prevalent polyphenol present in olives. Both *in vitro* and *in vivo* experiments have revealed its antioxidant potential of counteracting low-density lipoprotein (LDL) oxidation (Visioli & Galli, 1994; Visioli *et al.*, 2000). Evidence has also indicated that oleuropein has the ability to scavenge hypochlorous acid and nitric oxide (Visioli *et al.*, 1998). Several studies (Puel *et al.*, 2011; Khalatbary & Zarrinjoei, 2012) have also documented the anti-inflammatory and anti-cancer effects of oleuropein (Elamin *et al.*, 2013; Hassan *et al.*, 2013).

According to the Commission Regulation No. 432/2012 of the European Union (EU, 2012), olive oil is considered as protective of blood lipids from oxidative stress if it contains > 5 mg of hydroxytyrosol and its derivatives per 20 g of oil. In our study, the oil samples from OF1 (55.2 mg), OF2 (39.2 mg), and CF4 (29.8 mg) meet this criterion, but the organic oil samples had the highest amount.

It should be noted that we were only able to evaluate four oil samples in this report. At the same time, the phenolic profile of olive oil is also largely dependent on genotype (Vinha *et al.*, 2004). In addition, we have not evaluated the impacts on other aspects of the oil nutritional quality such as fatty acid composition. The higher concentrations of phenolic compounds in organic olive oil as reported in this study may not constitute a sufficient basis for drawing conclusions on the positive effects of organic farming with regards to human health.

4. Recommendations and limitations

In this study, we have developed a multi-criteria assessment framework for sustainable olive cultivation which is comprehensive, relevant, and relatively simple to implement. Based on our case study in Cyprus, we recommend organic olive growing with conservation practices (e.g. no-till, intercropping, cover cropping, etc.) and optimal irrigation decisions for improved economic, environmental, and human health outcomes. However, farmers and policy-makers may have to make context-specific trade-offs among the different indicators. Future applications of our framework in other olive cultivation systems is needed to test its sensitivity and robustness of sustainability assessment.

As mentioned earlier, the small sample size, cross-sectional measurements, and incomplete laboratory results have limited our ability to perform further analysis. For future studies, long-term monitoring of a larger number of olive orchards as well as measurements of other important factors (e.g. micro-climates, landscape heterogeneity, soil microbial community, etc.) are needed to disentangle the relative impacts of different farming practices and management systems on each sustainability indicator.

5. Conclusion

This study has adopted an integrated approach and proposed a multi-criteria framework with ten indicators for the sustainability assessment of olive cultivation under semi-arid climate. The case study in Cyprus has not only provided important empirical data for the potential benefits of organic olive cultivation, but also illustrated the great variability in sustainability performance within the same management system. In general, organic olive orchards possess higher abundance of soil arthropods, apply fewer synthetic chemicals of health concerns, and produce olive oils with higher concentrations of phenolic compounds, indicating a synergy between ecosystem and human health which has not been adequately addressed in previous studies. Organic olive growing is also likely to be more profitable given the similar oil yield but higher market price as compared to conventional counterparts. Our results also suggest that farming practices including no-till, intercropping, and cover cropping, seem to play a more essential role than the management systems on the soil fertility parameters and carbon sequestration capability in olive orchards. In addition, a moderate reduction in irrigation water also helps to enhance phenolic content in olive oil. These two findings highlight the potential climate co-benefits of sustainable agriculture as it may increase soil carbon stocks and improve water-use efficiency while ensuring other economic, environmental, and human health benefits. To sum up, we suggest organic olive cultivation using conservation practices and optimal irrigation decisions for sustainable agricultural development in the semi-arid areas in the Mediterranean Basin.

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Appendix A

Survey Questionnaire

Site No._____ Date: _______________

Farmer's Details:

Name: ________________ Age: ____________

Education: ______________

Current size of household: ______________

Size of land under operation: Total: ___________ acres

Olives: _________ acres, _________trees

1. Is your farm certified organic?
   - ☐ Yes, it was certified in _____.
   - ☐ No.

2. What olive varieties do you cultivate on your farm?

   ____.

3. Do you till your land?
   - ☐ Yes, conventional tillage since __________.
   - ☐ Yes, reduced tillage since____________.
   - ☐ No, no-till since _________.

4. Do you intercrop olive trees with other crops? If yes, with what crop and for how long?
   - ☐ Yes, with ______________________________________.
   - ☐ No.

5. Do you use cover crops in your orchard? If yes, what cover crops and for how long?
   - ☐ Yes, ____.
   - ☐ No.

6. Do you irrigate olive trees? If yes, what system (e.g. drip, sprinklers, etc.) do you use? How often and what's the water usage?
   - ☐ Yes,____
     ____
     ___________________________________.
   - ☐ No.

7. Do you apply pesticides to your land? If yes, please specify types and frequency. Please also mention if you use pesticides for other crops that are cultivated near the olives.
   - ☐ Yes,____
     ____.
   - ☐ No.

8. Apart from pesticides, do you use any of the following practices to control pests? If yes, please specify.
   - ☐ Biological control methods.
     ____
   - ☐ Integrated pest management (IPM) methods.
     ____
   - ☐ Physical or pheromone traps
     ____
   - ☐ Other methods.
     ____

9. Do you use fertilizers on your farm?
   - ☐ Yes, chemical fertilizers (specify types and frequency):
     ____
   - ☐ Yes, organic fertilizers of the following types (specify frequency):
     - ( ) Livestock manure______________________________
     - ( ) Poultry manure______________________________
     - ( ) Green manure______________________________
     - ( ) Other (specify) ______________________________
   - ☐ No.

10. How do you control weeds?
    - ☐ By grazing through animals
    - ☐ By mechanical weeding (tillage, mowing and/or manual)
    - ☐ By cover crops and/or intercropping
    - ☐ By chemical herbicides (specify, e.g. use of round-up)
      ____
    - ☐ Other (specify)______________________________________

11. How frequently do you prune the olive trees?
    - ☐ Less than once every two years
    - ☐ Once every two years
    - ☐ Once a year
    - ☐ More than once a year

12. What is your farm production of olives and olive oil in the past five years?
    ____
    ____

13. To whom do you sell your olive oil and what is the unit price?
    - ☐ Directly to consumers
    - ☐ Retailers
    - ☐ Wholesalers
    - ☐ Exporters
    - ☐ Processors
    - ☐ Governmental corporation
    - ☐ Other (specify) ________________

    Unit price: ______________________________