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Assessing Mediterranean agroforestry systems: Agro-economic impacts of olive wild asparagus in central Italy

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ABSTRACT

The intensification of Mediterranean farming systems has adversely affected the environment. As a result, climate change, soil and land degradation, and biodiversity loss have been exacerbated. A potential solution for addressing these challenges and enhancing farm sustainability is diversification, such as implementing agroforestry systems. Specific indicators are commonly used to evaluate the potential of diversification practices. However, agreement on a common set of assessment indicators is rarely reached. Moreover, the different biophysical and socio-economic conditions between regions make it difficult to adopt practices based on standardized assessments. This study aims at developing a practical methodology to assess the sustainability of Mediterranean agroforestry systems, using a three-dimensional evaluation concept for agro-environmental, economic and social performances. The steps in this study were, (i) define a set of relevant indicators and selection criteria, (ii) validate and select indicators through a participatory approach and (iii) apply the indicators to assess the performance of olive-wild asparagus agroforestry systems in central Italy. Expert opinions and stakeholders' participation were found to play an important role in identifying relevant indicators for assessing farming systems. The results showed that intercropping wild asparagus within olive orchards provides agro-environmental benefits and economic profitability, but also causes a higher workload. With a land equivalent ratio above one, the agroforestry system is more productive and results in a 50% higher income than olive sole cropping. With similar management practices, both systems had a comparable energy use efficiency and pesticide load index value. However, the annual workload, during the full production phase, increases by 75% in the agroforestry system mainly due to manual labor required for asparagus harvest. Furthermore, the agroforestry system had better economic resilience (positive net present value) in the face of drops in crop prices and rising production costs by up to 15%, whereas olive sole cropping generated negative net present value if costs increased by 10% or prices fell by 5%.

1. Introduction

The Mediterranean region has a long history of providing ancient civilizations with food, fiber, and fodder. This has led to a mosaic of multifunctional landscapes, reshaping the environment (e.g. terraces, ponds, etc.) (Pinto-Correia and Vos, 2004) and laying the social and ecological groundwork necessary for providing multiple ecosystem services (Wolpert et al., 2020). However, numerous Mediterranean landscapes are undergoing significant land-use changes due to increasing agricultural production, endangering crucial ecosystem services (Muñoz-Rojas et al., 2019). Current concerns include the depletion of water supplies, degradation of soils, the loss of biodiversity, and increasing social and economic challenges (Voltz et al., 2018). In addition, the region is facing an increasing magnitude and frequency of extreme weather events jeopardizing food security in a context of an increasing population (Muñoz-Rojas et al., 2019).

To reverse the current trend of deterioration and move towards higher levels of sustainability, innovative and sustainable farming

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practices are required (Muñoz-Rojas et al., 2019). One of the levers to reach this objective is diversification of cropping systems (Perrin et al., 2023). Agroforestry is a prominent diversification practice, that has a long tradition in the Mediterranean region dating back to pre-roman times (Pinto-Correia and Vos, 2004). Based on endemic tree species (e. g. oak, carob, olive, etc.), Mediterranean agroforestry systems form landscapes with intrinsic aesthetic values that are part of the cultural identity (Wolpert et al., 2020). The olive tree *(Olea europaea L.)*, emblematic of the Mediterranean, forms the basis of many traditional agroforestry systems that were common in the past (Katsoulis et al., 2022; Lauri et al., 2019). More recently, these traditional landscapes are subject to either abandonment or intensification, urbanization and niche market specialization by farmers aiming to avoid marginalization (Gennai-Schott et al., 2020). For example, only around 20.000 ha of Italian olive groves are still co-cultivated or grazed, mainly in Umbria and Lazio (Katsoulis et al., 2022). The current trajectories call for new concepts that are necessary to assure the viability of agroforestry systems while maintaining sustainable land use. Assessing innovative agroforestry systems at farm level, can inform whether these systems support a sustainable development pathway, leading to plans for their improvement and adaptation. In this regard, they are often seen as less profitable compared to sole intensive cropping and thus their adoption is hampered by farmer's needs to maximize profits (Tziolas et al., 2022).

To assess farming system's performance, sustainability indicators are acknowledged as established tools (Paul and Helming, 2019). Many sustainability assessment (SA) studies have been conducted for sole olive cropping systems, mainly through the methodological framework of Life Cycle Assessment (LCA) (Ben Abdallah et al., 2021; Fernández-Lobato et al., 2021; Guarino et al., 2019; Tsarouhas et al., 2015). Such standardized assessment methods facilitate comparison between studies and upscaling of results. On the other hand, local efforts to develop tools can reflect specific perspectives on sustainability assessment such as context relevant social dynamics. Such studies are still rare. However, generic assessment tools may be too narrow, focusing on specific aspects, and may underestimate the importance of other sustainability issues (Chopin et al., 2021).

While LCA studies focus on environmental impacts, social and economic performances of the olive value chain were seldom explored (El Joumri et al., 2023). As for olive agroforestry, despite the growing number of studies reporting their advantages, these studies remain limited to evaluating the feasibility, productivity, and interactions within the system components (Amassaghrou et al., 2023; Guesmi et al., 2022; Katsoulis et al., 2022; Mantzanas et al., 2021). In the rare studies dealing with sustainability assessment in olive agroforestry, the environmental dimension has usually been addressed using LCA (Paolotti et al., 2016; Tziolas et al., 2022), except in (Panozzo et al., 2022; Tziolas et al., 2022) who also assed economic dimensions.

Hence, a holistic approach is needed to assess environmental, social and economic impacts comprehensively. This can support reliability and relevance to a particular context, and may result in better acceptance of the results and greater likelihood of the implementation of new practices (Binder et al., 2010).

Although a range of sustainability assessment tools have been developed (Chopin et al., 2021), important challenges in sustainability assessment remain. These challenges can be summarized as: i) a lack of agreement on how impact areas and indicators should be selected, as well as on how many impact areas should be addressed in a specific context to justify sustainability statements (Chopin et al., 2021; Marchand et al., 2014). In fact, using indicators not relevant for a specific context can increase costs, make it more difficult to concentrate on the most important sustainability indicators, and cast doubts on the usefulness and credibility of sustainability assessments (Schader et al., 2014). ii) The imbalance regarding the ecological, economic, and social dimensions of sustainability in modeling and assessments, where the ecological aspect is generally favored, and iii) the rare involvement of stakeholders in the assessment process (Binder et al., 2010; Chopin et al., 2021).

Accordingly, the objectives of this study were: (i) to develop a systematic conceptual framework to assess the sustainability of Mediterranean agroforestry systems and (ii) to apply the framework to an agroforestry case study in central Italy. While developing the approach, we took into consideration, the balancing of agro-environmental, social and economic dimensions and involving stakeholders from the agroforestry sector in Italy and Tunisia.

2. Design of the sustainability assessment framework

This study presents the development of an approach to assess the sustainability of agroforestry systems in the Mediterranean region and its application to an olive-asparagus agroforestry system in central Italy (see Section 3.1). The approach entails creating a set of comprehensive assessment indicators that take into account the perspectives of social justice, economic viability, and environmental sustainability (Silva et al., 2020). The first step was to review the literature regarding Mediterranean agroforestry systems to define the system boundaries as well as to compile a comprehensive list of commonly used indicators. The second step was to validate the indicators drawn from the literature in a participatory approach with a stakeholder's opinion survey (Fig. 1).

2.1. Literature review

The literature review was carried out in two steps. The first step was to identify the assessment's system boundary, while the second step was to select indicators representing the agro-environmental, social and economic dimensions (Fig. 1).

The system boundary is "the thematic and spatio-temporal frame within which an assessment is conducted" (Paul and Helming, 2019). In the present work, the spatial scale covers the farm and plot level, as farmers make the strategic and operational management decisions that influence farm sustainability at this level (Chopin et al., 2021). The temporal scale of the analysis was set to 50 years. While some impacts (e. g. climate change) may occur at larger scales, they were not considered. The identification of the thematic boundary (biophysical, technical and socioeconomic factors, inputs, outputs and limits) is a determining attribute for any evaluation. In this study, literature and reports on Mediterranean farming system challenges were used to derive the attributes within a system (e.g. water, fertilization, etc.) that should be considered when choosing the indicators. The search term "(Mediterranean sustain* (agroforestry OR intercropping OR rotation*) AND (sustain* OR challenge)" was used in Google Scholar. Using Google scholar allowed us to access content that is not available in library databases, including preprints, theses, books and university repositories.

For the indicators compilation list, Web of Science (WoS) was used as it has curated, peer-reviewed content that is selected in accordance with publicly available standards. The search string "(ALL = ("selection" OR "choice") AND ALL = ("indicator" AND "sustainability" AND assess)" was used to search for literature in WoS Core Collection database in April 2021. The keyword "sustainability", was used to ensure that indicators used in the context of sustainability assessment were identified. The following qualification criteria were used to identify relevant literature for this review. We only considered i) literature published within the last decade (2010–2021), to ensure the relevance of indicators to current sustainability assessment practices, ii) literature focusing on the assessment of diversified farming systems (intercropping, diversified rotations and agroforestry), reflecting the intended scope of the study, iii) literature addressing all three sustainability dimensions, and iv) literature in English.

The references used for the selected articles were also checked for other relevant articles. These articles were screened using the following keywords: "selection", "indicator", "environmental assessment", "social assessment" and "economic assessment". If the use of any of these keywords showed that sustainability indicators were used, the paper was

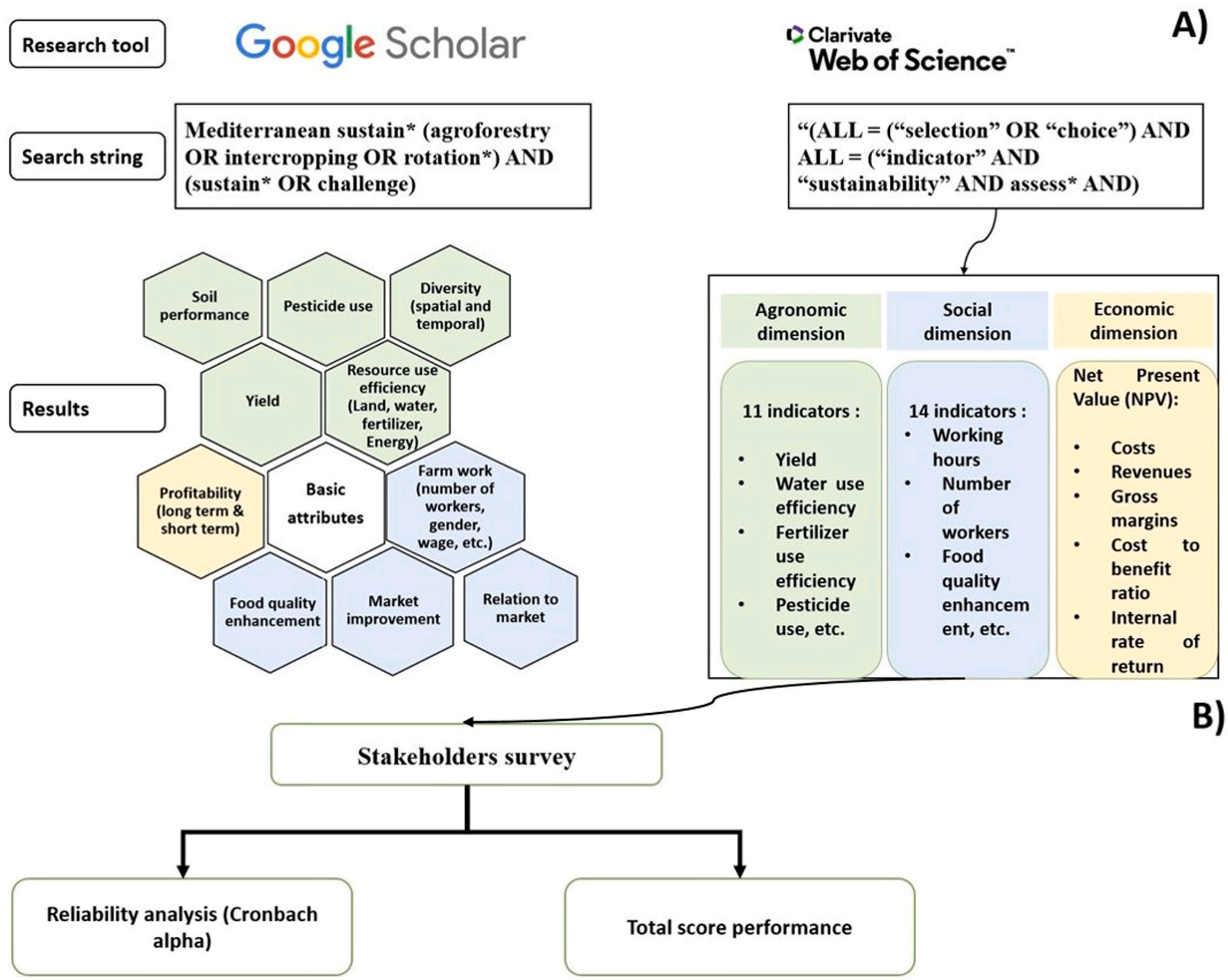

Fig. 1. Methodological steps. A) Literature review using google scholar to identify the thematic system boundary and literature review using Web of Science to compile the indicators list, B) Indicator validation with three criteria to calculate total score performance allowed by the reliability analysis (Cronbach alpha).

shortlisted for review. If not, the paper was excluded. A list of around 50 indicators from 25 initially identified articles was gathered and compared for relevance to the previously determined Mediterranean attributes (Fig. 1).

The body of the final literature that was shortlisted and reviewed in the current study consisted of 17 publications in total (Supplementary material, Table 1 A). The indicators representing basic attributes of farms in the area were retained. The basic attributes for indicators' selection for economic, social, and agro-environmental dimension of sustainability were developed based on site-specific features to the Mediterranean region. The basic attributes considered for the selection of the agro-environmental dimension concerned the productivity of the system and the inputs needed, in terms of water, fertilizer, energy and pesticide use. As for the basic attributes considered for the social dimension, they mostly focused on the human capital at the farm, e.g., the skills and trainings received of people working at the farm. The basic factors for the economic dimension concerned the profitability, which should be sufficient to compensate for the investment of the diversified system. Using these indicators, a survey was conducted.

2.2. Indicators validation

To validate the indicators of this study, "End-user validation" concept was followed, which entails whether an indicator is useful to a potential user (stakeholder) for making decisions (ul Haq and Boz, 2018).

The literature-compiled list of indicators, their definitions and their corresponding system sustainability dimensions were refined and validated in an iterative process with researchers with olive-based expertise, both in Italy (Council for Agricultural Research and Agricultural Economy Analysis) and in Tunisia (Olive Institute in Tunisia). Combined, the two countries produce 15% of world's olives (IOC, 2023) and offer two distinct socio-economic insights on olive production in the north and south of the Mediterranean. Regional stakeholders selected the final indicators for SA through an online survey in Italy (Italian) and Tunisia (Arabic). Experts from local research institutes in the Mediterranean countries sourced the group. Each indicator was scored based on three main characteristics: context relevance, clearness and ease of interpretation. Firstly, an indicator's context relevance is its ability to adapt to the local context (Corbière-Nicollier et al., 2011). Secondly, an indicator's clearness is its clarity in content and expression in coherent units. Thirdly, an indicator's ease of interpretation is its value being easy to understand by the user (ul Haq and Boz, 2018). The questionnaire survey measured the SA indicators' importance, using a five-point Likert scale ranging from 1 (least important) to 5 (very important). Furthermore, it was possible for the respondents to suggest additional indicators if they deem it necessary. Academics with backgrounds in Mediterranean farming systems pre-tested the survey for language and content authenticity.

The stakeholders received the questionnaire electronically. The period from June 2021 to December 2021 was used for the stakeholders' opinion survey. Upon low response rate, the survey was opened for a second round from March to May 2022. This survey explored people's perceptions regarding the initial set of SA indicators based on their respective criteria. The survey data was used to compute each indicator's total performance score.

When using a Likert-type scale, it is essential to report Cronbach's alpha coefficient of its items (indicators) for reliability. Reliability refers to the consistency of the produced scores. Ideally, a scored indicator would have a reliability coefficient of one, meaning that respondents 'scores perfectly reflected their true status with respect to the criteria being measured. However, a perfectly reliable test does not exist. Coefficients of 0.70 are usually considered adequate (Gay et al., 2014). In our case, indicators with a minimum Cronbach's alpha value of 0.70 were retained.

To obtain the total Likert scale score, the most common strategy is the sum of its item scores. The internal consistency allowed for application of summated rating principles whereby the indicator scores were calculated by summing up the responses from all criteria of each indicator as represented by Eq. 1 (Munyanduki et al., 2016). The indicator scores were then standardized into a percentage value based on highest possible performance score (See Eq. 1).

$$Si = \frac{\sum_{i=1}^{n} vi}{p * ni} * 100 \quad (1)$$

Where S_i denotes the total performance score of indicator i in percent, v_i denotes Likert score of criteria of indicator i, n_i denotes total number of criteria for indicator i, p denotes the highest possible score of the Likert response format. The conversion of the total indicator scores into percentage values then expresses the perceptions of the respondents as indicator performance scores (S_i) whereby the highest performance score would be 100% and the lowest would be 0%.

The survey results considered in this study refer to the practice of olive-wild asparagus agroforestry. Thirty-six respondents from Italy and Tunisia responded to the survey (supplementary material, Fig. 1 A). The stakeholders were not directly associated with the project, but rather they represented a wide range of mainly farmers, advisors and researchers with the common feature of being local actors in the agricultural field of each country. The Cronbach alpha values for the indicators were lower than 0.70 for one indicator which was not considered for the total score performance (supplementary material, Fig. 2 A). The total score performance was calculated by summing the scores from the three criteria (context relevance, clearness and easy interpretation) of each indicator. All the indicators scored above 50% were retained (supplementary material, Fig. 3 A) along with new indicators suggested by the stakeholders (supplementary material, Table 1 A). All the indicators had a total score performance above 50%, Tunisian scores were always lower than the Italian scores.

3. Application of the assessment approach to the case study

3.1. Case study description

We assessed the performance of an olive-asparagus agroforestry system in the Umbria region in central Italy by applying our participatory assessment framework. Olive growing is one of the most important agricultural activities in Italy, representing 56% of Italian farms and 76% of land used for permanent crops in 2010 (Iofrıda et al., 2020). Intercropping olive trees with wild asparagus (*Asparagus acutifolius* L.), a wild food plant naturally widespread in the Mediterranean region and producing edible spears used for millennia in local diets (Ferrara et al., 2011), has been proposed as a promising agroforestry practice in Italy (Mantovani et al., 2019; Rosati et al., 2021). Due to its natural dispersion, asparagus plants appear in small numbers and are irregularly positioned (Conversa and Elia, 2009), making it difficult for farmers to harvest the spears for market. When grown in regular rows and in sufficient quantities, this naturally occurring plant can be converted into a marketable product. Moreover, the system (intercropped asparagus with olive trees) is not yet adopted by farmers to a significant scale, and data is rarely available on the performance of its components (Paoletti et al., 2023). Currently, this type of system is only popular among hobby farmers within small-scale hilly farming systems. However, due to the decreasing profitability of intensive olive groves, we propose intercropping olive trees with asparagus for professional farmers as a commercial strategy to maintain traditional cultural landscape. The reference assessment period of 50 years is equal to the supposed economic life of the olive orchards (De Gennaro et al., 2012). The evaluation was based on a one ha area of olive orchard (Fig. 2). In this analysis, we considered two olive models. The Reference system (RS) as the sole olive cropping and the Agroforestry system (AF) as the diversified system (olive + intercropped wild asparagus). To perform the analysis, we built a technical database making some basic assumptions (Agricultural practices during the olive cycle) based on information coming from literature and experts (Table 1 & supplementary material, Table 2A-3A). According to the classification of olive life cycle stages proposed by De Gennaro et al. (2012) and Mohamad et al. (2014), the olive life cycle was divided into the following stages: (i) the planting year; (ii) the young phase from first year after planting until the 6th year, this stage is characterized by training pruning without significant production from olive trees; (iii) growing production phase from the 7th year (start of bearing) till the 11th year, when the tree continues to grow and is pruned to ensure both training and optimal production; and (iv) full production phase from the 12th year, when the production can be considered as being constant till the 50th year when olive yield starts to decrease. In this later stage, the tree is subjected only to productive pruning that ensures productivity and reduces the effect of alternate bearing. Each stage was associated with changes in agricultural practices to fit the plant development stages. Within each stage, agricultural practices do not differ significantly between RS and AF with regard to the growing of olives. During the first year of olive plantation, asparagus plants are assumed to be installed along tree rows, but not between, thus obtaining 5000 plants per hectare (unlike in the sole crops where 30,000 plants per hectare are planted). As perennial plant, asparagus produces yearly spears from the third year after plantation until the end of the assessment period. To help with the plant growth, the first two years will involve soil tilling twice a year, manual weeding and so-called "emergency" irrigation. The asparagus will be managed in the same way as the olive grove from the third year on. The distinction remains for asparagus harvest, practiced from late March to early May, and asparagus manual weeding operation required once a year.

In this study, most indicators are derived from information obtained through questionnaires with regional experts, literature reviews and simulation models. Data for this study were collected from: i) published studies in the same region (e.g., asparagus yield, management costs, etc.), ii) experts interviews (e.g. asparagus crop management), iii) public databases (Italian national statistical institute, etc.) for climate data and iv) simulation models (olive climate-based yield simulation model). The data set included information on management practices, use of fuel and lubricants, water consumption, quantity, type, period and distribution modality of fertilizers and pesticides, machinery used, labor hours, plant species, crop prices and wages.

The yield of asparagus plants was derived from published data for the sole crop by Benincasa et al. (2007), considering the lower planting

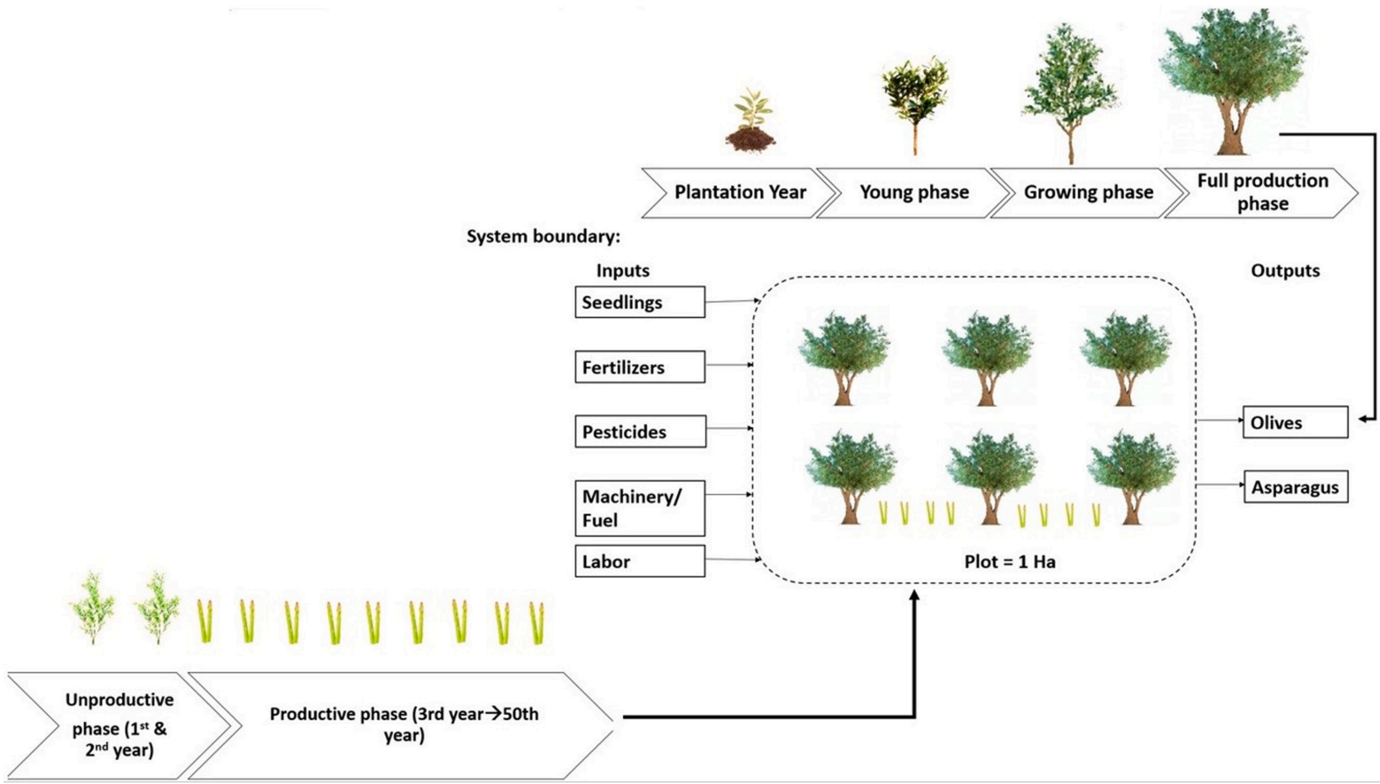

Fig. 2. Italian reference & agroforestry system assessment boundary along the olive life cycle.

Table 1
Main features of the reference and agroforestry systems.

Parameter	Reference system (RS) & Agroforestry system (AF)	Source
Cultivar	*Leccino*	(Proietti et al., 2014)
Planting density/ orchard layout	333 trees/ha (5.5 m × 5.5 m)	
Training system	Vase	
Pruning	Manual, annual	
Weed control	Green cover mowing	
Disease control	Copper	
Harvest method	Semi-mechanized (shakers)	
Economic life:		(De Gennaro et al., 2012; Mohamad et al., 2014)
-Young phase (YP)	1st-6th year (5 years)	
-Growing production phase (GP)	7th-11th year (5 years)	
-Full production phase (FP)	12th-50th year (38 years)	

density and a 33% reduction when plants are intercropped with adult olive trees (Paoletti et al., 2023).

When applying the sustainability approach to the Italian case study, indicator computation was hindered by data availability. In fact, data were not available for some indicators and, consequently, they were omitted from the list as scored by the stakeholders (supplementary material, Fig. 3 A). A summary of the indicators shortlisted for this study as well as the data sources used for the calculations are provided in Table 2.

3.2. Calculation of indicators

3.2.1. Agro-environmental indicators

The final list of agro-environmental indicators consisted of six indicators. The indicators olive yield and asparagus yield are self-explanatory, while the other indicators are described in this section.

To evaluate the overall productivity of the olive-asparagus system, the ***Land Equivalent Ratio (LER)*** (Mead and Willey, 1980) was calculated as:

$$\mathrm{LER}_{\mathrm{AF}} = \frac{tAF}{tRS} + \frac{vAF}{vRS} = LERt + LERv \tag{2}$$

Where $\mathrm{LER}_{\mathrm{AF}}$ is the overall LER of the agroforestry system, tAF is tree yield under agroforestry, tRS is tree yield under the reference system (RS), i.e., the monoculture, vAF is vegetable (asparagus) yield under agroforestry, vRS is asparagus yield under monoculture, LERt is the tree component of $\mathrm{LER}_{\mathrm{AF}}$, LERv is the vegetable (asparagus) component.

The energy input and output for the production unit area (one ha), expressed as MJ ha^{-1}, was calculated by multiplying each element of the inputs and outputs ($n = 1..11$) by the coefficient of equivalent energy (supplementary material, Table 4 A), as documented in the literature (Zahedi et al., 2015):

$$Energy_n = Element_n * \text{coefficient of equivalent energy} \tag{3}$$

Using the above equation, **energy use efficiency** (ratio of energy output to the energy input) and **energy productivity** (ratio of crops output to the energy input) were calculated while taking into account the evaluation of the entire system.

The pesticide load index (PLI) is defined as the amount of the applied product multiplied by the toxicity to non-target-organisms, and was calculated as:

$$PLI = PLHH + PLECO + PLFATE \tag{4}$$

The PLI has the unit "number of applications (toxicity doses) per ha and year. The PLI is constituted of three sub-indicators: the pesticide load (PLHH) for human health, the PL for ecotoxicology (PLECO) and the PL for the environmental fate (PLFATE). See more details in Kudsk et al. (2018).

Table 2
Shortlisted indicators for the analysis of the Italian case study.

Dimension	Acronym	Indicator	Unit	Data source
Agro-environmental	En1	Tree yield	kg year^{-1} ha^{-1}	Yield Model
	En2	Understory crop yield	kg year^{-1} ha^{-1}	Literature
	En3	Land equivalent ratio	-	Yield model, Literature
	En4	Energy use efficiency	-	Literature, experts
	En5	Energy productivity	kg MJ^{-1}	Literature, experts, yield model
	En6	Pesticide load index	-	Experts, Pesticide Properties Database (PPDB)
Social	So1	Working hours	h year^{-1}	Literature, experts
	So2	knowledge on diversified system (training hours)		
	So3	number of farms adhering to farm associations		
	So4	Gender equality	-	
Economic	Ec1	Cost	EUR year^{-1} ha^{-1}	Experts, literature
	Ec2	Benefit	EUR year^{-1} ha^{-1}	
	Ec3	Profit	EUR year^{-1} ha^{-1}	
	Ec4	Net Present Value (NPV)	EUR ha^{-1}	
	Ec5	Internal Rate of Return (IRR)	%	
	Ec6	Benefit to cost ratio (BCR)	-	
	Ec7	Labelling	-	Experts

3.2.2. Social indicators

Social sustainability indicators include impact areas such as labor issues (e.g. working hours) and available trainings (Popovic et al., 2018). For the application of this approach to the specific case study of Italy, we firstly considered the **average working hours (WH)** per management practice and per phase. Secondly, we considered the **number of training hours per year on agroforestry systems** as training and learning affect employee productivity. Thirdly, for external social interaction of the farm, we considered the **number of farmers adhering to farm associations** representing farmers, in order to ensure their participation in the formulation and implementation of policies and agricultural development actions. Finally, the **ratio of genders** calculated as the ratio of female employees to male employees was considered as an indicator for gender equality in farms.

3.2.3. Economic indicators

By estimating the associated economic impacts per hectare of inputs and outputs over a 50-year time horizon, equal to the supposed economic life of the olive orchards, the **Net Present Value (NPV)**, the **Internal Rate of Return (IRR)**, and the **Benefit-Cost Ratio (BCR)** indexes were calculated (Sgroi et al., 2015). The NPV, IRR and the BCR allow for comparison of land-use systems.

The net present value (NPV) in euros ha^{-1} is the difference between the present value of cash inflows and the present value of cash outflows over a period of time (Lambarraa et al., 2016). It was calculated as:

$$NPV = \sum_{k=0}^{n} \frac{CF_k}{(1+r)^k} \tag{5}$$

where CF_K represents the annual cash flow obtained from the difference between revenues and annual costs; k is the time of the cash flow; n corresponds to the duration of the investment (Sgroi et al., 2015). Following Lambarraa et al. (2016) we consider a discount rate “r” of 5% in the case of olive groves. If the NPV is > 0, the system generates profits over the time period considered. Conversely, where NPV < 0, invested funds are lost because the costs of investment outweigh the benefits. An overall positive NPV may not be sufficient to encourage the adoption of a new cropping system when access to credit is limited and working capital is minimal, because it is possible for producers to experience losses in any given year, despite an overall positive NPV.

The internal return rate (IRR, i.e. the annual return rate needed to make the NPV=0) was calculated by imposing:

$$\sum_{k=0}^{n} \frac{CF_k}{(1+r)^k} = 0 \tag{6}$$

The benefit cost ratio (BCR, i.e. the cost required for the farm to generate one euro of benefit) was also calculated:

$$BCR = \frac{\sum benefit\ Present\ Value}{\sum costPresent\ Value} \tag{7}$$

To provide a more comprehensive economic evaluation, we conducted a sensitivity analysis based on different scenarios related to price, cost and discount rate uncertainties. Firstly, by varying the discount rate from its basic value by 3%, the NPV was calculated for two scenarios with and without subsidies. Secondly, NPV, IRR and BCR indices were determined for each olive production system by varying its parameters by 5%, 10%, and 15% from their base values.

Moreover, **‘Labelling’** was considered as the number of obtained certificates by the farm (organic, protected designation of origin (PDO), etc.), the term label being reserved for officially recognized approaches. It highlights knowledge and agroecological production systems or other value propositions, like production system (organic, conventional) or seed sources. On the one hand, these labels represent a communication tool between the farm and the consumers and on the second hand a pledge of credibility and trustworthiness to the consumers that the products are of an important value to society.

3.3. Performance of the olive-wild asparagus system

3.3.1. Agro-environmental impacts

Since field-measured data on olive yields could not be retrieved for 50 years, a climate-based yield simulation model was used to generate yield data. The model used to predict yields during the full production phase, was an adaptation of the model developed by Arfaoui et al. (2021). The original model estimates olive yield as follows:

$$Yield = 0.06PAN\ \ hydro - 6.1T\text{min}\ \ SON\ \ (n-1) + 5.3T\text{min}\ \ August - 31.27 \tag{8}$$

where PAN hydro = the rainfall of the hydrological year (from September of the year preceding the harvest to August of the year of harvest); Tmin SON = nocturnal temperatures of September, October and November; n-1: year preceding the harvest; Tmin*August* is the nocturnal temperatures of August. Yields are expressed in quintals (1 quintal=100 kg). This model follows the olive production cycle starting in September of year n-1 when the soils begin to replenish their water reserves and ends in December of year n, when the harvest is more or less completed. However, this model does not account for alternate bearing in olive, whereby yields tend to alternate, because the previous year yield affects negatively the current year yield. This phenomenon has been analyzed and modeled by Bongi et al. (1995), so we added in the model the correction factor proposed by these authors. Additionally, the model estimates yield based on climatic parameters, but does not consider the radiation intercepted, and thus it does not respond to differences in light interception at varying plant density and/or local climate. Therefore, we recalibrated the modified model with local data from Famiani et al. (unpublished data), on a yield series of 6 years for a typical olive orchard in the Umbria region, as considered in this study. The final model was:

$$Yield = 0.06PAN \quad hydro - 6.1T\min \quad SON \quad (n-1) + 5.3T\min \quad August - 10.763 - 0.51D \tag{9}$$

where D (alternate-bearing factor) = yield (n-1) – average yield.

The model is based on climatic data from 1983 to 2021, and does not take into account planting density (333 trees/hectare) nor the loamy soil type, which are assumed constant. For the growing phase, the yield values are direct measurements from Rossi et al. (2019), as the data come from the same field considered as RS in this study.

The calibration of the model to the Italian climatic condition proved robust: with low root mean square error (RMSE=83 kg) and mean absolute error (MAE = 708 kg), and a high coefficient of determination (0.87). The average yields in the region are 8325 kg/ha (Chiorri and De Gennaro, 2012).

The olive yield over the considered olive life cycle is shown in Fig. 3. The first six years represented by the two phases (plantation and young phase) are of insignificant production from olive trees. The seventh year marks the start of bearing. The average yield of this period was 5600 kg ha^{-1} year^{-1}. The constant production phase marks a stable production that is affected only by the climate variation and the alternate bearing factor. During this period, the average yield was 8564 kg ha^{-1} year^{-1}, with the lowest being 6035 kg ha^{-1} year^{-1} and the highest being 11410 kg ha^{-1} year^{-1}. The olive yield is assumed the same for the RS and AF systems. In fact, asparagus, as an understory crop does not compete for light, nor for nutrients and water, as it is a wild plant producing little biomass, not different from the naturally occurring weeds in the RS, and because there are only 5000 plants under the olive orchard (as opposed to 30,000 plants in the asparagus monoculture). Regarding asparagus yield, the plants begin producing at full capacity from the third year after plantation (50 g per plant), as the olive trees are still young and light competition is minimal. However, the asparagus production capacity is reduced to 66% compared to sole cropping (33 g per plant) during the growing phase when the olive trees begin producing, assuming there is enough canopy to reduce light availability for the asparagus. The asparagus yield per plant for the sole cropping is assumed the same as for the initial part of the AF system, before shade reduces it (i.e. 50 g per plant).

The Land Equivalent ratio of the agroforestry system (LER_{AF}) (Table 3) was 1.16 between the third and seventh year of the olive life cycle. This value is greater than one due to the production generated by the asparagus (LERv = 0.16, Table 3), while olive yield is the same as the sole crop (LERt = 1). Asparagus in agroforestry is less productive than as a sole crop (LERv=0.16), due to reduced plant numbers (5000 instead of 30,000). After the seventh year, the LERv decreases to 0.11, due to shading by the trees, thus LER_{AF} stabilized at 1.11 for the remaining years.

Regarding the energy analysis, energy use efficiency (EUE) for RS and AF system was 3.95 and 3.29 during the growing phase, and 4.82 and 6.58 during the full production phases, respectively (Table 3). The first phases are characterized by high-energy inputs due to the installation of both crops, while there is no production. During the following phases, management practices are reduced, and the crops start to produce, explaining the increase in EUE. The energy productivity is higher for the AF system.

For the pesticide use, only copper hydroxide treatment is applied for olive trees starting from the growing phase during the rainy years to treat peacock eye disease, while no pesticides are applied to the wild asparagus. The PLI is 1.74 for both systems, with the main contributor being the PLHH.

3.3.2. Social impacts

The annual working hours (WH) in both systems vary according to the phases (Table 4). Orchard installation and asparagus transplanting, both manually performed, explain the relatively high WH at the beginning (78 h for the RS Vs 95 h for the AF). In the subsequent phases (from young to full production phase), most of the management practices require fewer WH as they are mechanized. Starting from the third year, asparagus enters its full production phase and the WH increase

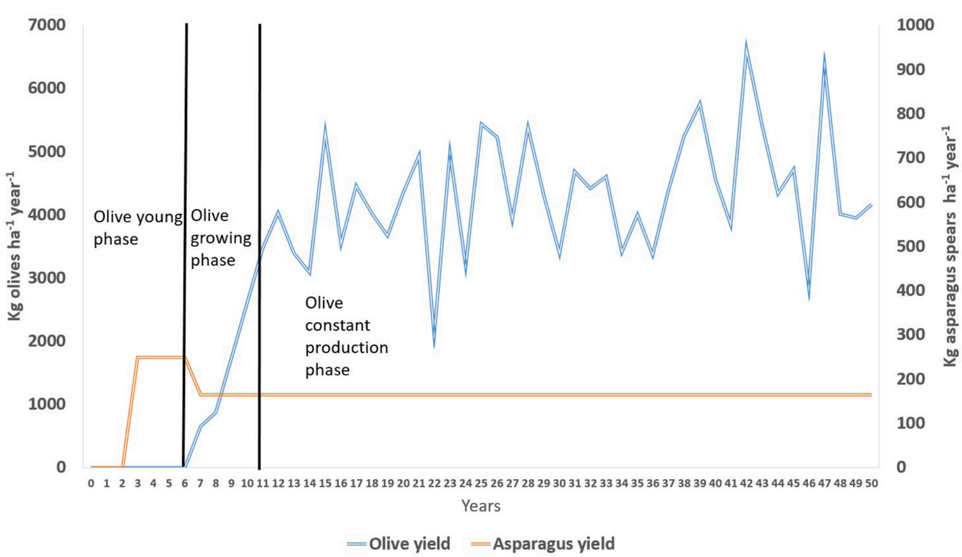

Fig. 3. EOlive & wild asparagus yield estimations (according to 50-year olive cycle).

Table 3
Agro-environmental performance of the RS and AF: Olive and asparagus yield per phase and Land equivalent ratio of the agroforestry system (LER_{AF}), its vegetable (asparagus) component (LERv) and tree component (LERt), and energy analysis per phase.

	RS				AF			
	Plantation phase	young phase	growing phase	full production phase	Plantation phase	young phase	growing phase	full production phase
Olive yield (kg ha^{-1})	N/A	N/A	5600	8564	N/A	N/A	5600	8564
LERt	N/A	N/A	N/A	N/A	N/A	1	1	1
Asparagus yield (kg ha^{-1})	N/A	1500	1500	1500	N/A	250	165	165
LERv	N/A	N/A	N/A	N/A	N/A	0.16	0.11	0.11
LER_{AF}	N/A	N/A	N/A	N/A	N/A	1.16	1.11	1.11
Energy productivity (kg MJ^{-1})	N/A	N/A	0.33	0.41	N/A	0.004	0.29	0.41
Energy use efficiency	N/A	N/A	3.95	4.82	N/A	0	3.29	6.58

Table 4
Working hours per management practice for the RS and the AF system during the four phases of olive cycle.

Agricultural practices	Plantation phase		Young phase		Growing production phase		Full production phase	
System	RS	AF	RS	AF	RS	AF	RS	AF
Plantation	78	95						
Pruning			20	20	20	20	21	21
Fertilization			3	3	3	3	3	3
Soil management			6	57	9	26	3	6
Fungi control					4	4	4	4
Harvest				66	15	58	30	73
Total	78	95	29	146	51	111	61	107

sharply as the harvest operation, done manually, requires higher labor. It is only later that the olive trees begin the full production. Despite the use of the motorized shakers, harvesting for the olives is still the most labor-intensive operation.

Regarding the indicator "knowledge on diversified system (Knowledge diversity)" represented by the number of training hours, the value is null throughout the olive cycle, as typically no training sessions are provided. The gender equality indicator is null, as the olive cultivation is typically done by male workers.

3.3.3. *Economic impacts*

The operational costs in the agroforestry system were 16% higher (400 EUR) on annual average than in the reference system during the full cycle (Fig. 4), mainly due to the costs related to the planting of asparagus (supplementary material, Table 5 A). The planting phase is the most costly of all phases, being 50% higher for the AF than for the RS. At full production phase, the costs for AF and RS are nearly the same with an average of 2760 EUR ha^{-1} $year^{-1}$. However, the AF system still have a 14% higher cost. The annual averages of revenues and net cash flows (Fig. 4) of the agroforestry system are also 1400 EUR higher than the reference system, throughout the whole cycle. Earnings from the AF system start in the third year due to asparagus production, while earnings for RS start from the seventh year due to the late olive production beginning. The revenues from the AF system are 32% higher during the full production phase compared to the RS.

Fig. 4. Economic performance of the RS and AF system. A) Total costs and revenues during the entire olive life cycle, B) Net cash flow of the entire olive life cycle.

The NPV of the RS (NPV_{RS}) is eight times lower than for the AF (NPV_{AF}), respectively, being 3412 EUR and 27,489 EUR, implying that the AF system generates greater financial returns over the olive life cycle. The Benefit-Cost Ratio (BCR) is always greater than unity for both systems (1.45 RS, 1.87 AF). This indicates that the present value of the expected benefits is higher than the present value of the costs. Therefore, both RS and AF system yield more benefits compared to their associated costs over the orchard's lifetime. Furthermore, the higher value of BCR_{AF} compared to the BCR_{RS} suggests that the AF system offers a relatively better financial return on investment. The IRR has values higher than current interest rates (5%) and it is around 6% for RS and 12% for AF. Therefore, both systems are expected to generate returns that surpass the cost of investment. Overall, these results indicate that both systems are financially viable, but the AF exhibits a higher benefit/cost ratio and offer better economic returns compared to the RS.

In addition, an analysis of the financial indices was conducted also assuming a public subsidy (supplementary material, Table 6A). In this case, the results demonstrate the convenience of AF system when compared to RS. In fact, NPV_{AF} was equal to 36,425 EUR, IRR_{AF} was 14% and the BCR_{AF} ratio was 2.07% compared to 12,349 EUR, 8% and 1.7%, respectively, without subsidies. Therefore, these results denote a lower risk management and higher farmer's income in AF compared to the RS.

The sensitivity analysis when adjusting the price, discount rate and production costs, by increasing and decreasing their values by 5%, 10%, and 15% (Table 5), have shown that the selling price of olive fruits produced with the RS gave negative NPV ($NPV_{RS} = -739$ EUR), even with price drops of only 5%.

Furthermore, the simulations show that the AF system is resilient even if there is a strong decrease in the selling price of the olives, or a sharp increase in the production costs of the olive grove. In fact, by decreasing the price of olive in the AF system by up to 15%, results are always positive and higher than those obtained with the RS (NPV_{AF} =14,458 EUR). The same holds true for a 15% increase in operating costs (NPV_{AF}=18,581 EUR). Thus, the AF system is economically resilient and able to absorb market shocks.

Concerning labelling, the region of Umbria provides the possibility to grow olives under a PDO label. However, at present the greatest majority of farmers do not adhere, therefore this option is not considered in the farm example in this study.

4. Discussion

4.1. The sustainability approach

Sustainability assessments rely heavily on metrics, and the choice of indicators may affect the outcome (Binder et al., 2010). Numerous index-based assessment methods have been described in the literature. However, none of these was tailored to sustainability assessments of olive-based agroforestry systems. To this end, we created an approach that shows high potential of describing in an integrative way the sustainability of Mediterranean agroforestry systems, while taking into consideration the knowledge and judgement of agricultural actors in the area. According to Notarnicola et al. (2017), sustainability assessment tools should respond positively to three questions: i) are the tools capable of integrating nature-society systems? Our approach included a three-dimensional set of indicators describing the farm in relation to its environmental, social and economic context. ii) Is the tool capable of assessing different scales or spatial levels? The approach created in this study considers both the farm and plot level of assessment. iii) Are the tools able to address both the short and long-term perspectives? The framework developed treats an agroforestry system over a 50-year period. However, indicators have been calculated as well in terms of yearly intervals. This gives the flexibility to assess the AF system development at smaller time steps, as well as the overview for the whole period. Nevertheless, this statement can only be applied to the current conditions, future scenarios cannot yet be fully accounted for.

Due to the lack of available data, the approach presented some limitations when applied to the Italian agroforestry system. In spite of several studies highlighting the biodiversity and resource efficiency of agroforestry systems, the effect of intercropping asparagus with olive orchards has not yet been sufficiently studied. Indeed, data to assess the indicators for biodiversity, resource use efficiency (water and fertilization), carbon footprint and labour issues originally validated or suggested by the stakeholders (supplementary material, Table 1 A) was not available. Possibly, this is due to the system's nature, which has not yet attracted much attention in the research community. Moreover, this could be due to the lack of official statistical datasets, as most land managers are not registered as farmers, enterprises and producers, so that it is difficult to know their practices (Gennai-Schott et al., 2020). Therefore, it is imperative to enrich and update the databases to provide more qualitative and quantitative results which are lacking even for olive sole cropping (El Joumri et al., 2023). Alternatively, it may be because stakeholders have been overlooked when choosing indicators for olive-based agroforestry system assessments, causing a discordance between what is being measured and what is important for them to be measured. Although the indicators were developed and answered to some extent to stakeholder expectations, there was still a lack of data for computing them in the specific case of olive-based agroforestry in the Mediterranean region. In this context, the focus of future efforts should be on addressing more concrete field needs. In particular, better reporting of social data would be useful, as it tends to be incomplete while it plays a fundamental role in the farming system.

Aside from this, there are still other inherent, unavoidable gaps with yield data for both crops in the long term considered for the case study. The yield model for olive trees has solved this problem. However, average values obtained from previous field measurements had to be used for asparagus. Unfortunately, no model can capture the full scope of the field's reality over 50 year's period in the context of changes in the future (harvesting technics, climate effects, etc.).

While all efforts were made to choose the indicators in a participatory approach with local stakeholders, the number of received responses is limited. It might have been larger and more diverse (in terms of stakeholder types) if the survey had been conducted directly and not sent online. In fact, advisors and policy makers are under-represented in this survey although being an important part of the value chain. Moreover, as stakeholders seemed to validate all the indicators presented to them, we are drawn to wonder if this is similar thinking to research efforts or if it was a passive way of responding. In future studies, the risk of bias could be reduced by applying different participation formats (e.g. through workshops).

While it is useful to involve stakeholders, there is inherent subjectivity in indicator scoring, as it may depend on the needs of a user,

Table 5
Sensitivity analysis of the two assessed systems with price and cost variation of + 5%, + 10%,+ 15% and − 5%, − 10%,− 15%.

Parameter	% Change	NPV		IRR	
		RS	AF	RS	AF
Price	-0.15	-4256.58 EUR	14,458.20 EUR	4%	9%
	-0.1	-2272.43 EUR	18,801.95 EUR	4%	10%
	-0.05	-739.21 EUR	23,145.69 EUR	5%	11%
	BASELINE	**3412.81 EUR**	**27,489.44 EUR**	6%	12%
	0.15	11,082.19 EUR	40,520.68 EUR	8%	15%
	0.1	8525.73 EUR	36,176.93 EUR	7%	14%
	0.05	5969.27 EUR	31,833.18 EUR	7%	13%
Cost	-0.15	10,570.27 EUR	36,397.26 EUR	8%	15%
	-0.1	8184.45 EUR	33,427.99 EUR	7%	14%
	-0.05	5798.63 EUR	30,458.71 EUR	7%	13%
	BASELINE	**3412.81 EUR**	**27,489.44 EUR**	6%	12%
	0.15	-3744.66 EUR	18,581.62 EUR	4%	9%
	0.1	-1358.84 EUR	21,550.89 EUR	5%	10%
	0.05	1026.98 EUR	24,520.16 EUR	5%	11%

suggesting that some people may be more interested in particular performance indicators than in others. In fact, both countries assigned performance scores were above the threshold of 50%, with the Italian scores being higher than the Tunisian scores. Possibly, because only researches and advisors responded to the Italian survey compared to the mixed sample of Tunisian respondents that included researchers and farmers who may not share the same viewpoints. However, such scoring differences cannot be attributed solely to stakeholder type, as other socio-cultural factors might be at play as well.

The present approach, regardless of the discussed limitations, is a first step towards assessing olive agroforestry sustainability. Compared to other existing approaches, it takes into consideration specific context of the studied region by involving the stakeholders in the choice of the metrics. While the survey was conducted in two countries, the Mediterranean region was treated as a homogenous agricultural entity, which is not entirely accurate when it comes to socioeconomics. The approach is also low-cost and could be quickly applied as most of the data come from publicly available resources. Nevertheless, omitting some indicators because the data is not publicly available reduced the scope of the assessment (not a full view of dimensions, especially the social dimension). For a comprehensive sustainability assessment, these data gaps would need to be addressed by possibly establishing a common database for such assessments similar to those already available for life cycle assessments.

4.2. The agroforestry case study

We found that there is a benefit in the AF compared to olive sole cropping while requiring similar management practices, except for higher labour requirements. The wild asparagus is endemic to the Mediterranean region and thus its cultivation requires very little input and knowledge, as the crop can survive without much intervention. While both RS and AF yielded similar amounts of olives, LER values were > 1 throughout the cycle, indicating a higher productivity of the AF system. This is consistent with other studies conducted in other Mediterranean countries with olive agroforestry. In fact, LER of olive agroforestry was > 1 in Morocco (Amassaghrou et al., 2021) and France (Panozzo et al., 2022) in association respectively with legumes and/or cereals. This suggests that olive-based agroforestry systems have greater productivity and land-efficiency than sole cropping, at least for the associated species and conditions studied so far. While the assumption that asparagus intercropping does not reduce olive yield appear plausible, given that the low plant density (5000 plants per hectare) results in a low vegetation biomass (Paoletti et al., 2023), more studies are needed to confirm this assumption.

The energy use efficiency (EUE) results show that both systems have output values greater than inputs. However, the EUE_{RS} is slightly higher than the EUE_{AF}. This is explained by higher energy inputs for the AF system while energy outputs do not increase as much due to the low amount of energy contained in asparagus. This indicator has not been considered yet in the analysis of olive agroforestry systems, making it hard to compare it with other studies. However, as this study shows, it is an important indicator to consider, especially considering the current energy crisis. In terms of energy productivity, the two systems show similar results (ratios < 1) suggesting that the production of 1 kg of goods requires more than one MJ of energy.

While pesticide use was limited to copper for olive trees, the PLI showed that this fungicide affects humans the most (PLHH=1.5), compared to other non-target organisms and environmental components. However, this value is much higher than what Rancāne et al. (2023) found for the same active substance used for apple trees (PLHH in apple trees=0.22).

The social dimension of sustainability was limited to a few indicators due to missing data for the computation of other indicators. For example, the AF compared to the RS needs more working hours. This is mainly driven by the addition of asparagus, a crop that is largely hand-managed, particularly for the harvest, which is time restricted and extremely time-consuming. This finding is similar to that of De Lapparent et al. (2023), which revealed that vegetables occupy most working hours while tree care activities requires little time. Higher demand for working hours could create additional employment opportunities, especially in small farms (i.e. the majority of olive farms) that employ only family members. However, in larger farms, finding workers might be difficult, compromising the harvested goods quality. Temporary migrant workers could therefore be hired, which would have other limitations, including work conditions and immigration restrictions. In olive cultivation, where male workers dominate the sector, intercropping asparagus would not result in major changes between the reference and agroforestry system, either suggesting that innovations in redesigning systems might not have such a significant impact on social aspects or that the change is governed by larger factors (historical, cultural, political, etc.). However, in a study by Gennai-Schott et al. (2020), women were found to constitute half of the farm managers in Tuscany.

The economic analysis has shown that the NPV for RS and AF is positive. Therefore, it is assumed that this investment will be profitable for RS as well as AF. Mohamad et al. (2014) determined an NPV for olive orchards in Italy at 15,118 EUR, which is higher than the NPV_{RS} found here. However, in the study of De Gennaro et al. (2012), NPV of olive orchards was − 32,249 EUR. This can be explained by the low olive prices (0.35 EUR per kg compared to 0.5 EUR per kg in our case). De Gennaro et al. (2012) suggested that olive prices should rise to 0.46 EUR per kg to obtain a positive NPV. However, the AF system has a better performance (NPV, IRR and BCR) than the RS. This result is mainly driven by the high price of wild asparagus in the studied area. A study by Kay et al. (2019) found that agroforestry landscape products had a higher market value than those from non-agroforestry landscapes. This was mainly due to the several tree products (such as olives and timber). Similar results were found in a study by Blanc et al. (2019), where all NPV values (based on benefits calculations) for four scenarios of walnut agroforestry systems showed positive results. This feature can be seen as a strength for the AF system in an olive market scenario characterized by high price uncertainty. In fact, in a price decrease scenario of up to 15%, the AF system is the only one to still generate a positive NPV (NPV= 14, 458.20 EUR), even with subsidies excluded.

Furthermore, the simulations show that the AF system is convenient even if there is a sharp increase in the production costs. In fact, by increasing the costs by up to 15%, results are always higher than those obtained with sole cropping (NPV = 18,581.62 EUR; IRR = 9; BCR = 2.21). These simulations confirm, therefore, that AF system has a better economic profitability even with strong decreases in selling prices of olives and in the absence of public subsidies. Similar results were found by De Roest et al. (2018) where European diversified systems performed equally well as specialized systems if not better. Despite these obvious economic benefits, asparagus spears are currently marketed from wild plants and its cultivation as an understory crop is yet to be spread.

Moreover, this profitability relies on the asparagus having a high culinary value in the entire Mediterranean region, while the rich niche market in Umbria region might not be available elsewhere. Therefore, the system studied here would not necessarily produce the same results in other regions, though the asparagus could potentially be substituted with other high-value local niche crops.

In addition, farmers do not use the local available labels, indicating their low profitability for the farmer. Creating labels for products derived from agroforestry systems, with both economic and social benefits, might represent an alternative opportunity to encourage the practice of agroforestry.

5. Conclusion

Sustainability assessment methods abound, but a comprehensive participatory assessment approach applied to Mediterranean agroforestry was lacking. Therefore, we developed our approach and found that involving stakeholders early in the assessment process integrates various perspectives on system function, as well as local knowledge about development aspirations and challenges. The stakeholders' views of the studied system influenced the definition of sustainability, the indicators used and the way the assessment was conducted. Despite the limitations of a stakeholder survey in comprehending holistically the sustainability of Mediterranean agroforestry systems, our approach represents a first step to understanding local stakeholders' concept of sustainability. It can be used to refine the definition of sustainability through an iterative co-learning process with diverse stakeholders. Hence, the novel approach fills the need for a method that is tailored to Mediterranean agroforestry systems. Although the indicators in this study may have specific significance in the Mediterranean context, the method itself can be replicated across other contexts. For the olive farming systems in association with wild asparagus in central Italy, we identified clear benefits for the environmental and economic aspects of sustainability compared to olive as a sole crop. However, the social dimension needs deeper investigation, especially concerning labor demand. The results of this study can be helpful to customize the agricultural practices to suit the various limitations and opportunities of Mediterranean farming systems. Finally, the results can be used to inform and support public policy makers responsible for designing and implementing agricultural programs in Italy and other Mediterranean countries with similar agroecological conditions.

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CRediT authorship contribution statement

Ferdaous Rezgui: **conceptualization, methodology, data curation, Writing-original draft, visualization** Adolfo Rosati: **validation, formal analysis, investigation, writing-review and editing** Fatima Lehnhardt (nee. Lambarraa) c**onceptualization, methodology, validation, writing- review and editing and supervision** Carsten Paul **validation and writing-review and editing** Moritz Reckling **conceptualizing, validation, resources, writing-review and editing, supervision, funding acquisition.**

Declaration of Competing Interest

The authors declare no conflict of interest.

Data Availability

The used data is included in the supplementary material.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2023.127012.

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