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A comprehensive assessment of diversified cropping systems on agro-environmental sustainability in three Mediterranean long-term field experiments

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ABSTRACT

The intensification of agricultural systems has caused a noticeable impact on agro-ecosystem services. Thus, the adoption of more sustainable agricultural practices such as crop diversification and reduction of external inputs represent an alternative strategy to minimize the impacts of intensive agricultural systems to the environment. This study aimed at evaluating the effects of crop rotation, conservation tillage, and low-input strategies on soil quality and farming performance using a set of 7 indicators based on a fuzzy logic approach. Data were collected from three Mediterranean long-term field experiments (LTEs) mostly oriented on cereal-based and vegetables cropping systems, located in Spain and Italy. The selected agro-environmental indicators clearly discriminated both from a geographical point of view and between monoculture and diversification, showing their suitability for the evaluation of diversified cropping systems. Such indicators highlighted that implementing crop diversification and reducing soil disturbance and chemical inputs enhanced soil quality. In this context, the most significant effects of diversified cropping strategies were the increase of crucial variables such as soil organic carbon (SOC), total nitrogen (TN), available phosphorus (P_{av}), and bulk density (BD) maintaining a stability of yields in all the three LTEs. These results provide strong evidence for the benefits of crop diversification in Mediterranean areas, highlighting that diversification represents a very promising strategy for more sustainable land management. Simple and composite indicators calculated using fuzzy method can be proposed as tool to assess the effects of diversification strategies on cropping systems performance. This approach can be used to define local solutions to help the re-design of cropping system through crop diversification transition across Europe.

1. Introduction

Agricultural intensification (AI) is characterized by specialization and/or simplification of traditional farming practices, generally based on increased use of external inputs, mainly energy, agrochemicals, and intense mechanization in order to maximize crop productivity (Ruiz-Martinez et al., 2015). An increase in AI in the rural areas showed a simplification of the environment caused by the removal of natural landscape elements such as isolated trees and hedges (Debolini et al., 2018). Thus, AI systems often negatively affect the environmental integrity. It is well-known that intensive use of irrigation and nitrogen (N) fertilization may cause water scarcity (Xu et al., 2020), nitrate contamination (Perego et al., 2012), increase of greenhouse gas (GHG) emissions (Sanz-Cobena et al., 2017), loss of biodiversity (Kehoe et al., 2017), and a decline in soil fertility, by increasing soil degradation (Lal et al., 1990). In some views, environmental sustainability and intensification seem incompatible and contradictory (Robinson, 2004, Garnett et al., 2013).

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Fig. 1. Location map of three long-term field experiments (LTEs) in Spain (ESA= Spain Arable, ESH=Spain Horticulture) and Italy (ITA=Italy Arable).

With reference to European Mediterranean areas, arable systems are often highly specialized and mostly oriented on cereal-based intensive cropping systems, in monocropping or short-rotation with other rainfed or summer irrigated crops such as processing tomato (*Solanum lycopersicum* L.), forage-based systems, or other mixed succession also including bare fallow (Di Bene et al., 2016; Francaviglia and Di Bene, 2019).

The adoption of crop diversification strategies defined as the application of rotation, intercropping, and multiple cropping (Hufnagel et al., 2020), encompassing alternative management practices, e.g., reducing tillage intensity, organic and mixed fertilization, crop residue retention, and water use efficiency encompassing an appropriate soil and crop management, can enhance the resilience to environmental stresses, with positive and variable effects on biodiversity and ecosystem services as highlighted also by Beillouin et al. (2021). Thus, diversification of cropping systems, is an essential steps towards a sustainable, lower input production (Nicholls et al., 2016) by minimizing environmental and social impacts of agriculture while not reducing yield and income. Indeed, sustainability is an issue that needs social, economic, and environmental dimensions to be addressed within a complex framework of indicators (Bockstaller et al., 2015).

In such progressive technical change and learning process, farmers gradually improve the diversification of cropping systems by modifying some agricultural management practices over a long period (Meynard et al., 2012; Chantre and Cardona, 2014). Despite the widespread consensus on the benefits of crop diversification and reduction of inputs in intensive and simplified farming systems (Beillouin et al., 2021; Rodriguez et al., 2021), the adoption of such systems is still limited, due to several constraints such as the lack of knowledge on new/uncommon crops, not affordable technical solutions (e.g., costs of machinery or new labour organization), and out of market products (i.e., market uncertainty and lack of reward by higher prices for the products).

In the H2020 Diverfarming project (www.diverfarming.eu), sustainable and diversified cropping systems were defined, including also low-input farming practices. A multidisciplinary approach to assess real benefits and drawbacks for implementing diversification strategies across Europe was adopted. In this context a network of 16 case studies (CSs) and 8 long-term field experiments (LTEs) covering 6 agri-environmental zones has been identified across 6 countries. The CSs and LTEs were selected to achieve several goals. These include the sound use of natural resources (soil and water) and external inputs (e.g., fertilizers, pesticides, energy, and machinery), reduction of soil and water pollution, GHG emissions, and erosion rates by increasing soil organic carbon (SOC) sequestration and biodiversity, as well as increasing farm productivity and economic benefits by reducing production costs and favouring social acceptance of diversified cropping systems by facilitating the adoption of more sustainable value chains. In this study we present the results of three Mediterranean long-term experiments belonging to the Diverfarming network, in terms of agro-environmental and economic sustainability. The three cropping systems were diverse, both for pedoclimatic and socio-economic conditions and cropping systems, ranging from horticulture to cereal-based systems. In this context, a strict comparison of measured variable was not suitable to describe and summarize the overall effect of diversification across Mediterranean systems. To this end, a set of indicators was built to evaluate the effects of diversification and to summarize results among the different analysed. Indeed, indicators are useful tools for interpreting and summarizing the complexity of the impact of alternative scenarios of practices (Bockstaller et al., 2008). Generally, an indicator refers to quantifiable and measurable attributes of a system, used to supply information on other variables or processes that are difficult to assess or describe. Since a single indicator cannot meet all the requirements, a set of indicators can describe key attributes of agroecological systems (Dale et al., 2004). The use of composite indicators addressing different aspects of a complex system is often discussed, due to the loss of information and the methodological problems involved. A major problem in the case of composite indicators is “adding apples and pears”, but the identification and transparent weighting of the different components convey the relative importance of the various aspects of sustainability (Rigby et al., 2001). Several methods are available to

Table 1
Description of the crop management in the different pilot areas during the growing season 2017/18.

Country	Region	Code	Crop management	Type of crop
Italy	Apulia	ITA-1	Rotation under No-Tillage	Tick bean-durum wheat
		ITA-2	Monocropping under No-Tillage	Durum wheat
		ITA-3	Monocropping under Conventional Tillage	Durum wheat
		ITA-4	Rotation under Conventional Tillage	Tick bean-durum wheat
Spain	Murcia	ESH-1	Rotations and multicropping under conventional management	Melon-cabbage
		ESH-2	Rotations and multicropping under organic management	Melon-cabbage
		ESH-3	Rotations and multicropping under biodynamic management	Melon-cabbage
	Aragon	ESA-1	Rotation under conventional tillage	Barley-winter wheat
		ESA-2	Rotation under no-tillage	Barley-winter wheat

weight the components of a composite indicator, like the normalization technique in monetary unit or physical unit, the multivariate approach, and the fuzzy logic (Bockstaller et al., 2008). In this study, we have adopted a fuzzy expert system, since it allows to aggregate dissimilar variables into composite indicators, and such system can be applied to uncertain and imprecise data, including subjective judgments. In this study, for the first time, effects of crop diversification and low-input strategies were evaluated using data collected from three Mediterranean long-term experiments and using a set of 7 indicators based on a fuzzy logic approach for the assessment of the performance.

2. Materials and methods

2.1. Study areas

Three LTEs were selected in the Mediterranean South (Spain) and Mediterranean North (Italy) environmental zones (Fig. 1), namely ESH (Spain horticulture), ESA (Spain arable), and ITA (Italy arable), respectively.

ESH is located in Campo de Cartagena, in the Region of Murcia (South-East Spain), where the mean annual temperature is 17.5 °C, the mean annual precipitation is 231 mm, and the annual potential evapotranspiration is 1300 mm. ESA is located in Huesca, in the Region of Aragon, and is characterized by a mean annual temperature of 13.4 °C, a mean annual precipitation of 327 mm and an annual potential evapotranspiration of 1197 mm. ITA is in Foggia, in the Apulia Region, where the mean annual temperature is 15.8 °C, the mean annual precipitation is 529 mm and the annual potential evapotranspiration 734 mm.

The ESH experiment focuses on horticulture rotations (melon and cabbage) and intercropping (oat), comparing conventional, organic, and biodynamic management (Table 1). The long-term experiment started in 2012 and monitored for this study until 2018. Three different farms for each management were selected within the Murcia Region, with a size of 10–30 ha, located in proximity and with the same crop's history. For organisational purpose, farms are divided into different sectors or plots of about 1 ha from which three plots for each farm were selected. Therefore, 9 replications per management were obtained: 3 farms per management (conventional, organic, and biodynamic) x 3 independent plots per farm. Melon (*Cucumis melo* L.) in summer and cabbage (*Brassica oleracea* L. *var. sabellica)* in winter were cultivated in all plots for season 2017–2018. The previous crops in the rotation were: *Apium graveolens* L. / *Cucumis melo* L. (2016/2017), *Lactuca sativa* L. / *Brassica oleracea* L. var. Italica (2015/2016), *Apium graveolens L./ Cucumis melo* L. (2014/2015), *Brassica oleracea* L. var. Italica / *Capsicum annum* L. (2013/2014), *Foeniculum vulgare* Mill. / *Cucurbita moschata* Duchesne ex Poir. (2012/2013). Oat (*Avena sativa* L.) and vetch (*Vicia sativa* L.) were introduced as cover crops only in the ESH3, grown between the two main crops and incorporated in the field in April/May before summer crop establishment. The crop cycle length for winter and summer crops was approximately 10 months, from first days of October to end of July. The residues in all treatments were incorporated in the field with CT, up to 30 cm depth.

Table 2
Soil Clay (Cl), and sand (Sa) content (0–30-cm depth), and texture according to the USDA classification for the considered sites (Apulia, Murcia, and Aragon) and crop managements.

Site	Soil-management (code)	Cl (%)	Sa (%)	USDA
Apulia	ITA-1	16	32	Silt loam
	ITA-2	17	32	Silt loam
	ITA-3	21	31	Loam
	ITA-4	16	32	Silt loam
Murcia	ESH-1	16	40	Loam
	ESH-2	20	42	Loam
	ESH-3	17	46	Loam
Aragon	ESA-1	18	16	Silt loam
	ESA-2	23	10	Silt loam

Where:
ESH-1: Rotations and multicropping under conventional management, ESH-2: Rotations and multicropping under organic management ESH-3 Rotations and multicropping under biodynamic management in the Murcia (ES) region;
ITA-1: Rotation under No-Tillage, ITA-2: Monocropping under No-Tillage, ITA-3:Monocropping under Conventional Tillage, ITA-4Rotation under Conventional Tillage in the Apulia (IT) region;
ESA-1: Rotation under conventional tillage, ESA-2, Rotation under no-tillage in the Aragon (ES) region

In 2017/2018 melon was transplanted in April and manually harvested between July and August. Brassica was transplanted in November and harvested manually in February. The ESH1 was fertilized with sheep manure and inorganic mineral N fertilizer under fertigation and chemical control for pest/diseases. The ESH2 included sheep manure, soluble organic fertilizers for fertigation, and biological control of pests/diseases. The ESH3 included sheep compost, soluble organic fertilizers and compost tea for fertigation, biological control of pests/diseases, and cover crops.

In ESA, the experimental area was 0.5 ha out of 4 ha in a rainfed arable farmland. The long-term experiment started in fall 2010. The area is divided in three blocks where field crops were cultivated under two tillage managements, reduced tillage (15 cm depth with disk ploughing and cultivator) and no tillage. During the first 4 years, a barley (*Hordeum vulgare* L.) monocropping was the dominant cropping system, but from 2014 onwards a four-year rotation pea (*Pisum sativum* L.) -barley-wheat (*Triticum aestivum L.*)-barley rotation was in place. Fertilization includes 75 kg N ha− 1 yr− 1 applied as an inorganic fertilizer in both management practices. Harvest was carried out in June for all crops with a combined machine. All crop residues were left in the field.

In ITA, the long-term experiment started in 1994 for tillage/no tillage with continuous durum wheat (*Triticum durum Desf.*), while in 2009 two-year durum wheat (*Triticum durum Desf.*) - tick bean (*Vicia faba L.*) rotation (wheat/tick bean) was introduced in each tillage/no tillage plot. The experimental design is a strip-strip plot adapted to technical needs, e.g. commercial machinery used for the no tillage seeding and justified by the large experimental area (2 ha). Tillage and no tillage are main plots (strip) and in the subplot monocrop with continuous durum wheat or tick bean-durum wheat rotation are compared. The replicates are obtained by subdividing the subplots in 5 areas georeferenced where samples are collected each year for monitoring. Spatial variability is accounted for by using geostatistical methods (data not reported). In the tillage a mouldboard ploughing to 30 cm depth followed by a disc-harrow and flexible harrow seedbed preparation was carried out each year. In no tillage plots seeding with proper machinery was conducted. Basal dressing in the conventional

Table 3
Description of the indicators included in the Integrated Sustainability Index with the parameters used in the fuzzy analysis.

Indicator	Type of index	Input data*	Fuzzy parameters		
			Unfavourable limit	Favourable limit	Weight
AWC	Complex	SWFC, SWW	0.06	0.18	5%
SOC	Single	SOC	8	17	20%
BD	Single	BD	1.6	1.1	10%
NI	Complex	pH, EC, TN, P_{av}, Ca_{ex}, Mg_{ex}, Cu_{ba}, Zn_{ba}, Fe_{ba}, Mn_{ba}	1	0	20%
CDI	Complex	II, CVI	1	0	20%
YI	Single	Crop yield or Marketable yield	0	1	25%

AWC: Available water capacity; BD: Bulk density; Ca_{ex}: Exchangeable calcium; CDI: Crop diversification index; CVI: Crop variability index; Cu_{ba}: Bioavailable copper; EC: Electrical conductivity; Fe_{ba}: Bioavailable iron; II: Intensification sequence index; Mg_{ex}: Exchangeable magnesium; Mn_{ba}: Bioavailable manganese; NI: Nutrient index; TN: Total nitrogen; P_{av}: Available phosphorus; SOC: Soil organic carbon; SWFC: field capacity, SWW: wilting point; YI: Yield index; Zn_{ba}: Bioavailable zinc.

Table 4
Input data for complex soil nutrient index (NI).

Soil variable	Unit	Unfavourable limit	Favourable limit
pH	[dimensionless]	5.5	8.5
EC	[dS/m]	4	0.5
TN	[g/kg]	0.8	2
P_{av}	[mg/kg]	5	150
Ca_{ex}	[cmol/kg]	1	60
Mg_{ex}	[cmol/kg]	0.5	8.3
Cu_{ba}	[mg/kg]	2	500
Zn_{ba}	[mg/kg]	0.5	500
Fe_{ba}	[mg/kg]	2	250
Mn_{ba}	[mg/kg]	0.5	500

EC: Electrical conductivity; TN: Total nitrogen; Pav: Available Phosphorus; Caex: Exchangeable calcium; Mgex: Exchangeable magnesium; Cuba: Bioavailable copper; Znba: Bioavailable zinc; Feba: Bioavailable iron; Mnba: Bioavailable manganese.

tillage plots was carried out before the secondary tillage for seedbed preparation, providing 36 kg N ha-1 plus 96 kg P_2O_5 ha-1, as diammonium phosphate (18–46–0), whilst in no tillage plots the same fertilizer was spread on the surface. The seeding rate was set to 350 vital seeds m^{-2}. Top dressing (64 kg N ha-1 as ammonium nitrate) was applied in both plots at 21–29 tillering stage, according to BBCH scale (Hess et al., 1997), followed by an application of specific herbicides for grasses and broadleaf weeds. In no tillage plots the weeds were controlled before sowing with glyphosate. The wheat straw was removed from the field. Tick bean was desiccated by a non-selective herbicide in May, at the 65 full flowering stage according to BBCH scale, then chopped and either scattered on the soil surface in no tillage plots or incorporated with tillage in tillage plots (in autumn).

Soil textures for different pilot areas are presented in Table 2.

2.2. Data collection

2.2.1. Field samples

In this study, data were collected from the three LTEs during the growing season 2017/18.

Soil samples were collected at two depths (0–10 and 10–30 cm), using manual augers (3 subsamples per point) and they were introduced in labelled plastic bags for the transportation and following processing (drying, sieving, and analysis).

In each area three composite samples per two depth were collected per each sub-plot, i.e. 54, 36 and 40 for ESH, ESA and ITA respectively for the soil analysis. For both the bulk density and hydraulic properties, three undisturbed cores per each analysis and depth were collected at the same points as before. The main soil physico-chemical parameters analysed were: soil texture by particle size analysis (like sand, silty and clay percentage); bulk density by core sampling method (g cm^{-3}); pH and electrical conductivity (EC) were measured in H2O in Italy and in deionized water (1:5 w/v) in Spain; soil organic carbon (SOC g kg^{-1}, LECO TOC Analyzer, mod. RC-612; LECO Corporation, 1987); total N (N_{tot} g kg^{-1}, LECO Nitrogen analyser FP-528, St. Joseph, MI); exchangeable K (K_{ex}, in mg kg^{-1}); bioavailable P, Fe, Cu, Zn, Pb, Cd, Ni, As (in mg kg^{-1}), extracted by Mehlich 3 method (Mehlich 1984) and analysed by simultaneous plasma emission spectrophotometer (ICP-OES Iris; Thermo Optek, Milano, Italy). The soil water content at wilting point (SWW) and soil water content at field capacity (SWFC) were calculated using the retention curve method (Van Genuchten, 1980), in which moist samples were dried by raising the air pressure in an extractor with a porous ceramic plate.

In the three LTEs, soils were sampled and analysed using the procedure described in Álvaro-Fuentes et al. (2018). For the indicators' calculation, the soil data used were averaged using a weighted mean of the two depths.

2.2.2. Description of selected soil properties and relative indicators

A set of simple (SOC, BD and YI) and complex indicators (AWC, NI and CDI) (Table 3) was selected and aggregated into a more comprehensive Integrated Sustainability Index (ISI), in order to assess in a wide and synthetic perspective the cropping system management effect. Outputs of this composite indicator range between 0 and 1, where 0 is the maximum positive value and 1 is the minimum negative value according to the sustainability criteria addressed by the indicator.

As mentioned above, data refers only to one growing season, but the study areas are long-term experiments and consequently data collected account for long term effects. Gathered data are compared only inside cropping systems of the same case study, since the variation of pedoclimatic conditions from ESH to ESA and ITA would bias any comparison among case studies.

Available Water Capacity (AWC) expresses the soil's ability to retain water and to make it sufficiently available for plant use. AWC is the water held in soil between its field capacity (FC) and permanent wilting point (WP) (Bruand et al., 2003), calculated as follows:

$$\text{AWC} = \text{field capacity - wilting point} \qquad (1)$$

The soil water contents at FC and WP were obtained in undisturbed soil cores (100 ml). The samples were saturated from the bottom and balanced at pressures of 33 and 1500 kPa; both pressures were obtained in pressure plates (Richard's apparatus). Following extraction, soil cores were weighted and oven dried at 105 °C for 24 h; moisture content as per cent of weight and volume was calculated by difference of weight. The range of AWC positive values used in this study is between 0.06% and 0.18% of soil weight for loamy soils (ISNP, 1982).

Soil Organic Carbon (SOC) is the carbon component of soil organic matter (SOM), is about 58% of its mass, and is widely used as an indicator of the organic matter content in soils and sediments. SOM is linked with important soil properties as water retention, fertility and nutrients availability, filtering and buffer capacity, soil biodiversity, etc. Values ranged from 8 to 17 g C kg^{-1}: values lower than 8 are considered unfavourable for all types of texture, while values higher than 17 are positive for loam, silt loam texture (MIPA, 2000).

Bulk density (BD) is a single indicator of soil compaction. BD reflects the soil's ability to function as structural support for water and solute movement, and for soil aeration. Thresholds shown in Table 3 indicate ideal values for plant growth.

To evaluate the fertility status of soils, different soil chemical

Table 5
Indices, variables and values defined by expert group.

Index	Variable	Final value	Mean	Median	Mode1	Mode2
Soil Nutrition index (SNI)	Acidity-pH [dimensionless]	15	14.4	15	15	5
	Electrical conductivity-EC-[dS/m]	10	8.1	10	10	
	N content-Nt-[g/kg]	20	19.1	20	20	
	P available-P_{av}-[mg/kg]	15	15.6	15	10	
	Exchangeable Ca-Ca_{ex}-[cmol/kg]	10	9.4	10	5	10
	Exchangeable Mg-Mg_{ex}-[cmol/kg]	10	8.1	10	10	
	Cu bioavailable-Cu_{ba}-[mg/kg]	5	6.6	5	5	
	Zn bioavailable-Zn_{ba}-[mg/kg]	5	6.9	5	5	
	Fe bioavailable-Fe_{ba}-[mg/kg]	5	7.8	5	5	
	Mn bioavailable-Mn_{ba}-[mg/kg]	5	6.9	5	5	
Crop diversification index (CDI)	Intensification index (II)	60	51.3	50	60	40
	Crop Variability index (CVI)	40	48.1	50	30	60
Integrated Sustainability index (ISI)	Soil Nutrition index (NI)	20	19.7	20	20	
	Crop diversification Index (CDI)	20	21.3	20	20	
	Bulk density (BD)	10	11.3	10	10	
	Soil Organic Carbon (SOC)	20	20.9	20	20	
	Available Water Capacity (AWC)	5	10.3	10	10	5
	Yield index	25	20.3	25	25	

properties including pH, electrical conductivity, available N, P, exchangeable Ca and Mg and available micronutrients were measured. They were all included for calculating the Soil Nutrient availability index (NI) that defines the capacity of soil to supply nutrient to plants (Singh et al., 2016). NI was calculated by a fuzzy calculator using the same inputs (Table 4) described by Amara et al. (2017). The NI ranges between 0 and 1, where 0 is favourable and 1 unfavourable.

To have a wide picture of the effect of diversification, two more indicators indirectly related to soil protection and agrobiodiversity were considered: Crop Diversification Index (CDI) is a complex index, calculated using two simple indicators: Intensification sequence Index (II) and Crop Variability Index (CVI). II is the ratio between the months in which soil is covered by crops and total months of the year (Sasal et al., 2010) or total months of a rotation period (i.e., 36 months in a three-years rotation). II has values between 0 and 1, where 0 is unfavourable (means no crop in the field for 12 months) and 1 is favourable, with the soil covered for all the year. This indicator is a proxy to estimate the soil protection against erosion of the cropping system. CVI is calculated as the ratio between 1 and the number of crops growing in a year or years of rotation. Values equal to 1 indicates that there is a monoculture, while a value equal or lower than 0.5 indicates the presence of a rotation. CDI has values between 0 and 1, where 0 is favourable and means that the area is covered by crops in rotation and a cover crop for all the year or rotation period, while 1 is an unfavourable value corresponding to a monocrop with some months of bare soil during a year or rotation period.

Sustainable cropping systems assessment cannot disregard the productive performance, and normally yield is the parameter considered. In our case the Yield Index (YI) is a simple index obtained as the ratio between the crop yield of the crop in the diversified system and the yield of the reference crop, i.e., the conventionally managed crop in our study. The unfavourable limit is 0 and the favourable one is 1. In this study, the reference yield for Spanish ESH data was calculated as the average of the values of the 3 sub-plots managed in the conventional way (ESH_11, ESH_12, ESH_13), while for ITA and ESA the reference value is equal to the value of conventional tillage with monocrop for Italy (ITA_3) and rotation under conventional tillage for ESA_1.

2.2.3. Fuzzy analysis

In this study, a set of indicators was used to build up a metric for a quantitative assessment of the soil overall compliance to sustainability requirements. The input indicators were constituted either by measurable physical variables or by composite indicators. Both the simple and composite indicators were then further aggregated into a unique and comprehensive dimensionless indicator termed Integrated Sustainability Index (ISI). A two-stage fuzzy aggregation procedure was designed following the method of Bellocchi et al. (2002) to calculate both the input composite indicators and the final indicator.

Since the theoretical and computational details of the method are available in the seminal publication (Zadeh, 1965 and 1978) while application examples can be found in other relevant publications (Rivington et al., 2005; Silvestri et al., 2006: Diodato and Bellocchi, 2007; Confalonieri et al., 2010; Garofalo et al., 2018), only a brief and intuitive description will be reported here.

The adopted fuzzy procedure is based on the multi-valued fuzzy set theory introduced by Zadeh (1965) and follows the so-called Sugeno or Takagi–Sugeno–Kang method of fuzzy inference (Sugeno, 1985). A relevant feature of this technique is its robustness on uncertain and imprecise data, such as subjective judgments used in this study, and the capability of aggregating dissimilar measures in a consistent and reproducible way (Bouchon-Meunier, 1995; Ross, 2004).

With respect to the sustainability concept, for each input variable two functions were defined to quantify the degree membership to two fuzzy subsets, i.e., Favourable (F; compliant to sustainability criteria) and Unfavourable (U; non-compliant to sustainability criteria). The membership degree varies between 0 (full non-membership) and 1 (full membership), as described by two complementary *S-shaped* quadratic functions (Liao, 2002). Application of the functions requires the specification of limit values beyond which membership values take 0 or 1 values with absolute certainty, i.e., for a given variable, this consist in specifying at which value it is undoubtedly “good” or “bad” relative to sustainability.

Aggregation of variables is then performed by formulating a set of fuzzy-based logic rules to connect all the possible combinations of F and U values into a final global value. A decision rule consists of associating an expert weight to a given conjunction of inputs. In plain words, the reasoning runs as follows: if all input variables are F, the value of the indicator is 0 (maximum sustainability level), whereas if all indices are U, the value is 1 (lowest sustainability level). The output of all decision rules is “truth values”, which are finally combined as weighted average in a global value.

In setting up the decision rules we had to decide on the relative importance of each input, by attributing an expert weight to each of them. Definition of limits and weights is ultimately the crucial step in capturing and formalising experts’ knowledge. In principle, a specific expert weight should be assigned for each fuzzy set combination, so, for n variables to aggregate, a n^2 number of weights are required. To ease the task of assigning weights, it was decided to define only one importance weight to each individual input variable, and then to derive the specific weight of each combination by linear interpolation of variable weights, as described in Silvestri et al. (2006).

All the weights reported in Tables 3 and 4, used for calculating the

Table 6

List of variables (mean and standard deviation), II and CV indexes (dimensionless) and yields (kg/ha). (AWC: Available water capacity (dimensionless); BD: Bulk density (g/cm^3); Ca_{ex}: Exchangeable calcium (cmol/kg); CDI: Crop diversification index; CVI: Crop variability index; Cu_{ba}: Bioavailable copper (mg/kg); EC: Electrical conductivity (dS/m); Fe_{ba}: Bioavailable iron (mg/kg); II: Intensification index; Mg_{ex}: Exchangeable magnesium (cmol/kg); Mn_{ba}: Bioavailable manganese (mg/kg); TN: Total nitrogen (g/kg); P_{av}: Available Phosphorus (mg/kg); SOC: Soil organic carbon (g/kg); Zn_{ba}: Bioavailable zinc (mg/kg), pH:acidity (dimensionless)).

	ESH-1		ESH-2		ESH-3		ITA-1		ITA-2		ITA-3		ITA-4		ESA-1		ESA-2	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
AWC	0.11	0.03	0.12	0.03	0.14	0.02	0.10	0.01	0.11	0.02	0.11	0.01	0.10	0.02	0.11	0.03	0.11	0.02
pH	8.44	0.14	8.76	0.08	8.48	0.17	7.97	0.19	7.97	0.19	7.98	0.17	8.00	0.14	7.92	0.14	7.49	0.22
EC	0.54	0.09	0.37	0.06	0.47	0.16	0.13	0.01	0.14	0.006	0.14	0.007	0.15	0.006	0.23	0.09	1.35	0.77
TN	0.97	0.23	1.10	0.30	1.22	0.36	1.26	0.11	1.27	0.26	1.06	0.11	1.19	0.15	1.43	0.36	1.45	0.36
P_{av}	16.15	5.53	17.41	7.19	17.93	11.78	304.75	30.5	281.46	68.6	263.59	83.5	258.70	65.7	5.62	2.5	6.77	3.18
Ca_{ex}	8.53	0.74	8.80	2.51	8.71	2.32	76.74	10.7	69.16	9.7	70.73	9.6	77.85	6.3	4.28	0.62	7.37	2.8
Mg_{ex}	3.48	0.27	3.58	0.95	3.65	0.83	3.31	0.08	3.17	0.09	3.21	0.22	3.34	0.25	0.39	0.08	1.03	0.88
Cu_{ba}	1.98	0.67	2.37	0.60	2.95	0.57	9.98	0.80	8.02	2.81	8.39	4.07	8.80	2.73	4.00	0	4.00	0
Zn_{ba}	4.05	2.62	5.13	1.25	5.23	1.17	20.02	13.26	10.72	11.3	7.47	3.6	7.13	0.77	4.00	0	4.00	0
Fe_{ba}	5.57	3.53	3.15	0.9	6.73	8.52	129.09	14.09	109.89	42.41	103.75	55.9	117.35	40.42	5.00	0	5.00	0
Mn_{ba}	8.85	1.39	5.09	1.58	6.25	2.13	447.11	72.2	295.31	164.7	257.45	168.5	293.11	123.6	7.00	0	7.00	0
BD	1.32	0.11	1.35	0.13	1.35	0.12	1.22	0.13	1.15	0.10	0.94	0.06	0.91	0.05	1.43	0.12	1.31	0.08
SOC	10.67	1.37	11.02	3.43	12.87	3.28	16.59	0.49	16.34	0.72	16.24	0.57	17.08	0.79	9.90	2.2	10.96	5.09
II	1.00	–	1.00	–	1.00	–	0.67	–	0.67	–	0.67	–	0.67	–	0.75	–	0.75	–
CVI	0.50	–	0.50	–	0.25	–	0.50	–	1.00	–	1.00	–	0.50	–	1.00	–	1.00	–
Yield	87,650	–	84,347	–	85,340	–	2183	–	2673	–	2713	–	2437	–	3330	–	4205	–

Where:

ESH-1: Rotations and multicropping under conventional management, ESH-2: Rotations and multicropping under organic management ESH-3 Rotations and multicropping under biodynamic management in the Murcia (ES) region;

ITA-1: Rotation under No-Tillage, ITA-2: Monocropping under No-Tillage, ITA-3:Monocropping under Conventional Tillage, ITA-4Rotation under Conventional Tillage in the Apulia (IT) region;

ESA-1: Rotation under conventional tillage, ESA-2, Rotation under no-tillage in the Aragon (ES) region

complex indices, were defined by a survey carried out with a group of 20 European experts in soil science and agronomy (81 % and 19 % respectively). They were asked to answer a simple questionnaire in which they had to give a value to the single indicator, taking into account its importance in the context of crop diversification, according to their experience (Table 5). The final value was defined not only on the average of results, but mostly by using modal values.

2.3. Statistical analysis

All statistical analyses were performed using the R software (R Core Team, 2020), packages FactoMineR (Lê et al., 2008) and FactoExtra (Kassambara and Mundt, 2017). Mean and standard deviation (SD) were computed for the dataset of indicators. A principal component analysis (PCA) was performed to better explore similarities and differences among the diversification strategies implemented in the experimental sites and the performances obtained by the set of indicators. Active variables were only the seven indicators; the other variables (e.g., pH, micronutrients) were used as supplementary variables to interpret the dimension of variability. Then a Hierarchical Clustering on Principal Components (HCPC) was performed using the Ward's criterion on the first three principal components. The aim of the HCPC function was to perform clustering and to use the complementary variables between clustering and principal component methods to better highlight the main features of the data set. The number of classes (*k*) was found by comparing results of multiple runs with different number of classes and visualizing the grade of clustering in a graph.

3. Results

3.1. Performance of the diversified cropping systems

In all the 3 areas crop diversification favours the increase of some variables such as TN, P_{av}, SOC and BD (Table 6).

As shown in Table 6, in Spain, in Murcia region, ESH-3 (biodynamic management) presented an increase of TN (+26 %), for P_{av} (+11 %), BD (+2 %) and for SOC (+21 %) compared to ESH-1. (conventional management). In Aragon region, no-tillage (ESA-2) increased TN by 1.3 %, P_{av} by 20.4 % and SOC by more than 10 % compared to tillage (ESA-1). In Italy, the rotation system with no-tillage (ITA-1) showed an increase by about 19 % for TN, 15 % for P_{av}, 30 % for BD and 2 % for SOC, with respect to the monocrop with conventional tillage (ITA-3). II index has equal values within the same areas, because the numbers of months of the crops in the field are the same; meanwhile CVI has positive values in the multicropping experiments (Table 6).

In all areas, the diversified cropping system showed an increase of Ca_{ex} and Mg_{ex} values, as for the micronutrient variables in ESH and ITA (Table 6).

In ESA-2 crop yield was greater than ESA-1 (+21 %), whereas in ESH and ITA diversified management has less productivity than the conventional management − 3.7 % for ESH-2, − 2.6% for ESH-3 and in Italy − 20 % for ITA-1, − 1 % for ITA-2 and − 10 % for ITA-4 respectively (Table 6). The AWC index (Fig. 2) showed an increase in ESH, with a higher value in the conventional management than in the two sustainable cropping systems; in ESA there was no difference between tillage and no-tillage management. In ITA, there was a positive difference between monocrop with tillage (ITA-3) and monocrop with no-tillage (ITA-2), i.e., 0.68 and 0.60 respectively. Values were similar between ITA-3 and ITA-1 (0.68 and 0.71 respectively), and higher in rotation with conventional tillage in ITA-4.

The NI increased in ESH and ESA (Fig. 2): in ESH, the values were 0.52, 0.50 and 0.47 respectively for rotations and multiple cropping under conventional, organic, and biodynamic management. In ESA it had a better value for conventional tillage than no-tillage management. In ITA the values ranged from 0.38 in monocrop with conventional tillage (ITA-3) to 0.33 in rotation under no-tillage (ITA-1). NI presented

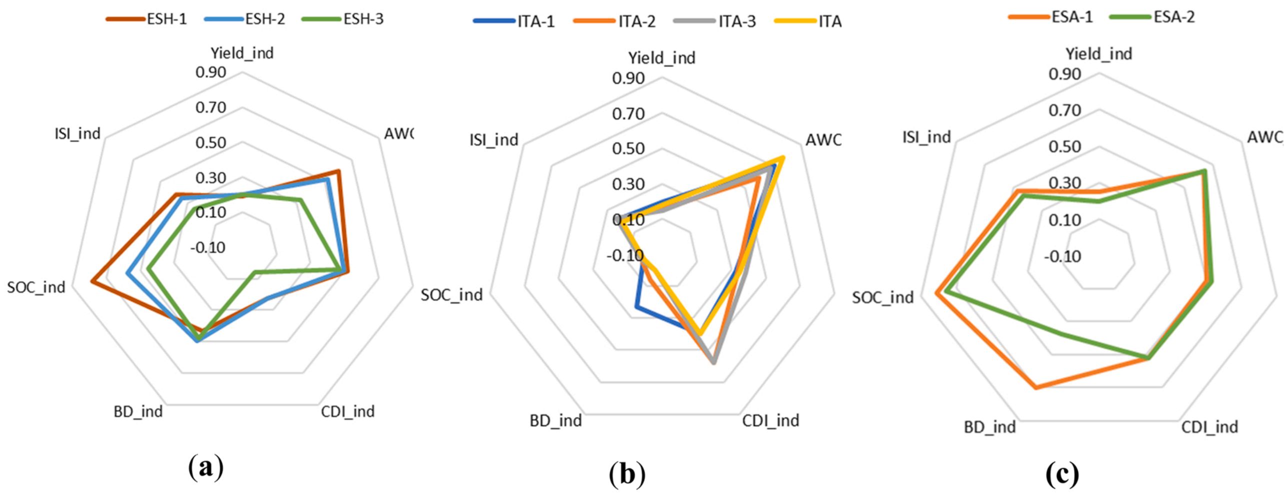

Fig. 2. Indicator's representation differentiated between different cropping systems in Murcia (a), Apulia (b) and Aragon region (c). (AWC_ind = Available water capacity index; BD_ind = Bulk Density index; CDI_ind= Crop Diversification index; ISI_ind= Integrated Sustainability index; NI_ind= Nutrition index; SOC_ind= Soil Organic Carbon index). ESH-1: Rotations and multicropping under conventional management, ESH-2: Rotations and multicropping under organic management ESH-3 Rotations and multicropping under biodynamic management in the Murcia (ES) region; ITA-1: Rotation under No-Tillage, ITA-2: Monocropping under No-Tillage, ITA-3: Monocropping under Conventional Tillage, ITA-4Rotation under Conventional Tillage in the Apulia (IT) region; ESA-1: Rotation under conventional tillage, ESA-2, Rotation under no-tillage in the Aragon (ES) region.

Table 7
Principal Components information.

	PC1	PC2	PC3	PC4	PC5	PC6
Eigenvalue	3.44	1.55	0.90	0.66	0.28	0.17
Variance (%)	49.10	22.12	12.85	9.43	4.04	2.39

a value less than 0.52, thus revealing that generally soil in the study area had a good capacity to supply nutrients to the plant, in particular in the Italian site. This is probably due to the higher value of SOC, available micronutrients, available phosphorus and exchangeable Ca in comparison to the other sites.

The CDI gave an idea of the diversification management; in all the study areas there was an improvement in the CDI with crop rotation: In ESH, CDI was 0.23 for ESH-1 and ESH-2, and 0.06 in ESH-3. In ESA, it was obviously the same across the two experiments because they have the same cropping system. In ITA the value was 0.58 for the monocrop field, while the ITA-1 and ITA-4, characterized by rotation, had a CDI of 0.40.

The SOC index showed positive results in almost all the study areas, being 0.78 and 0.45 in ESH-1 and ESH-2, respectively. In ESA the index has positive values, with 0.81 in ESA-1 and 0.76 in ESA-2. In ITA, SOC index showed similar values among the different cropping system management.

The final index, the Integrated Sustainable Index, had favourable values in all the study areas (Fig. 2): in the Spanish field experiments the values of the indicator were − 0.38, 0.35 and 0.25 for ESH-1, ESH-2, and ESH-3, respectively; and were 0.47 and 0.43 for ESA-1 and ESA-2, respectively. In the Italian study area, the field with monocropping under conventional tillage had a higher value for ISI in comparison with the field with rotation.

3.2. *Principal component analysis*

The PCA allowed to better interpret the agronomic performance of the different cropping systems. The PCA performed on the indicators and input variables provided high fractions of explained variance for the first three principal components (about 84.1 %): 49.1 %, 22.1 % and 12.9 % respectively for the first, the second and the third one (Table 7). The first component is mainly described by the SOC, the NI and the final indicator (ISI), i.e., 26.29 %, 23.88 % and 26.08 %, respectively; the second component is characterized by the CDI (45.86 %) and the third one by AWC and Yield indicators (47.51 % and 40.53 % in that order) (Fig. 3 and Table 8).

As explained above, PC1 is influenced mainly by soil characteristics, while PC2 by the cover crop and diversification. In the upper right quarter of the PCA space (Fig. 3 light purple area), there are data with low performance of SOC, NI and ISI and low diversification; in the lower right quarter of the PCA space (Fig. 3 yellowish area), there are data with poor soil characteristics, but good crop diversification: In the lower left quarter (Fig. 3 yellowish area) are represented good quality soils together with diversification. Finally, in the upper left quarter (Fig. 3 light green), data have good soil characteristics and low diversification.

A clear separation between field case data is shown: ESH-2 and ESH-3 are present in the lower quarters, all ITA data are concentrated in the upper left quarter, due to the fact that in the Italian case study higher values of SOC and micronutrients (Table 6) are observed. ESA-1 in semiarid rainfed conditions with poor soil characteristics is present in the upper right quarter.

3.3. *Cluster analysis*

Fig. 4 shows the dendrogram by hierarchical cluster analysis (Ward's method) on principal components, using all the predictors (standardized to 0 mean and unit variance). A total of seven clusters are identified.

Individuals in cluster 1 include all the data of ITA-1 and ITA-4 that are characterized by a rotation management system together with good soil characteristics (Table 9). Cluster 2 includes all data of ITA-2 and ITA-3 (monocropping) and few data of ESA study area, defined by rainfed small grain crops either with tillage or no-tillage management. Individuals in cluster 3 include all data of ESH, in particular ESH-2 and ESH-3, the most diversified cropping systems. Cluster 4 and 5 includes mainly ESH data. Cluster 6 include mostly ESA-2 data, defined by rainfed small grain crops with no-tillage management, while ESA-1 data are included in Cluster 7 with also ESH ones.

4. Discussion

4.1. *Cropping system diversification*

The overall effect of cropping system diversification and input

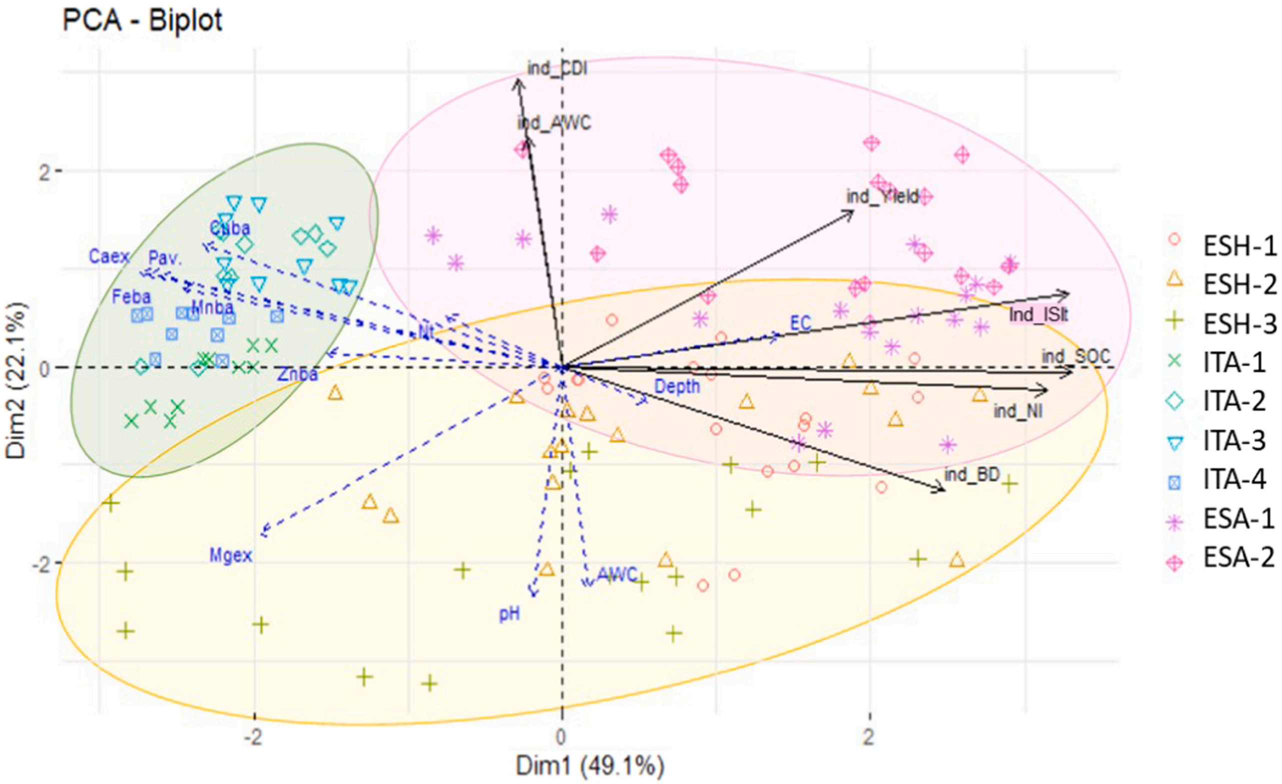

Fig. 3. Principal component analysis on the seven indicators (ind_CDI, ind_AWC, ind_Yield, ind_ISI, ind SOC, ind_NI, ind_BD), showing the first two principal components, explaining respectively 49.1 % and 22.1 % of the total variance. The light purple area represent data with low performance of soil characteristics and low diversification, in the yellowish area data have poor soil characteristics and good crop diversification and in the green area data have good soil characteristics and low diversification. (ind_AWC = Available water capacity index; ind_BD = Bulk Density index; ind_CDI= Crop Diversification index; ind_ISI= Integrated Sustainability index; ind_Yield= Yield index; NI_ind= Nutrition index; SOC_ind= Soil Organic Carbon index; ESH-1: Rotations and multicropping under conventional management, ESH-2: Rotations and multicropping under organic management ESH-3 Rotations and multicropping under biodynamic management in the Murcia (ES) region; ITA-1: Rotation under No-Tillage, ITA-2: Monocropping under No-Tillage, ITA-3: Monocropping under Conventional Tillage, ITA-4Rotation under Conventional Tillage in the Apulia (IT) region; ESA-1: Rotation under conventional tillage, ESA-2, Rotation under no-tillage in the Aragon (ES) region.).

Table 8
Variables that most contributed to each component (%) (ind_AWC = Available water capacity index; ind_BD = Bulk Density index; ind_CDI= Crop Diversification Index; ind_ISI= Integrated Sustainability Index; ind_Yield= Yiedld index; ind_NI= Nutrition Index; ind_SOC= Soil Organic Carbon index).

	Dim.1	Dim.2	Dim.3
ind_Yield	8.6	13.4	40.5
ind_AWC	0.1	29.1	47.5
ind_NI	23.9	0.3	0.02
ind_CDI	0.2	45.9	1.5
ind_BD	14.8	8.4	7.9
ind_SOC	26.3	0.02	0.05
Ind_ISI	26.1	2.9	2.5

reduction in fields with different pedoclimatic conditions, soil and crop management practices was assessed, considering some commercial farms in Mediterranean countries. Our purpose was not to compare the effect of a single management practice, as, for instance, no-till vs. conventional tillage or continuous monoculture vs. crop rotation, but to provide a comprehensive picture of the whole system by means of a set of indicators. In this framework, the diversification proved to be able to improve the soil characteristics, as shown by the increase of AWC, NI, BD, and SOC indices, to enhance erosion protection (CDI index), whereas farmers' income (yield index) remains stable. Similarly, previous studies showed that the amount of SOC was affected by the management (Liu et al., 2021; Alijani et al., 2012; Spargo et al., 2008; Khorami et al., 2018). In this framework, Hendgen et al. (2020) found that SOC value was higher in the biodynamic systems compared to the integrated management, and this is consistent with our observations in ESH.

In ITA, coupling crop rotation and conservation tillage showed a positive impact on soil characteristics, confirming the findings by Bai et al. (2016), and Troccoli et al. (2015). In particular, they highlighted that the legume used in the rotation maintains or increases soil organic matter and provides biologically fixed N. Similarly, Khorami et al. (2018) and Feng et al. (2014) showed higher values of SOC and TN in no-tillage, as we observed in ITA and ESA. Francaviglia et al. (2019) showed that, compared to monoculture, longer crop rotations (3–5 years) and the introduction of legumes resulted in higher increases in SOC contents (18%), at Mediterranean sites, as in ESH and ITA, and that SOC content increased in no-till management compared to the conventional one, as in ESA. Our findings about BD index confirmed the thesis by Gozubuyuk et al. (2014), affirming that no-till increases both physical soil properties (bulk density, penetration resistance) and hydraulic soil properties (field capacity, field water content and infiltration rate).

The YI results are in line with Troccoli et al. (2015), that indicated a reduction of yield in the first years of transition from conventional agriculture to conservation agriculture, and with Ruisi et al. (2014), that evaluated how in the dry and less productive years no-till was more yielding than conventional tillage - as in ESA. Tamburini et al. (2020) confirmed that diversification enhances biodiversity, pollination, pest control, nutrient cycling, soil fertility, and water regulation without compromising crop yields.

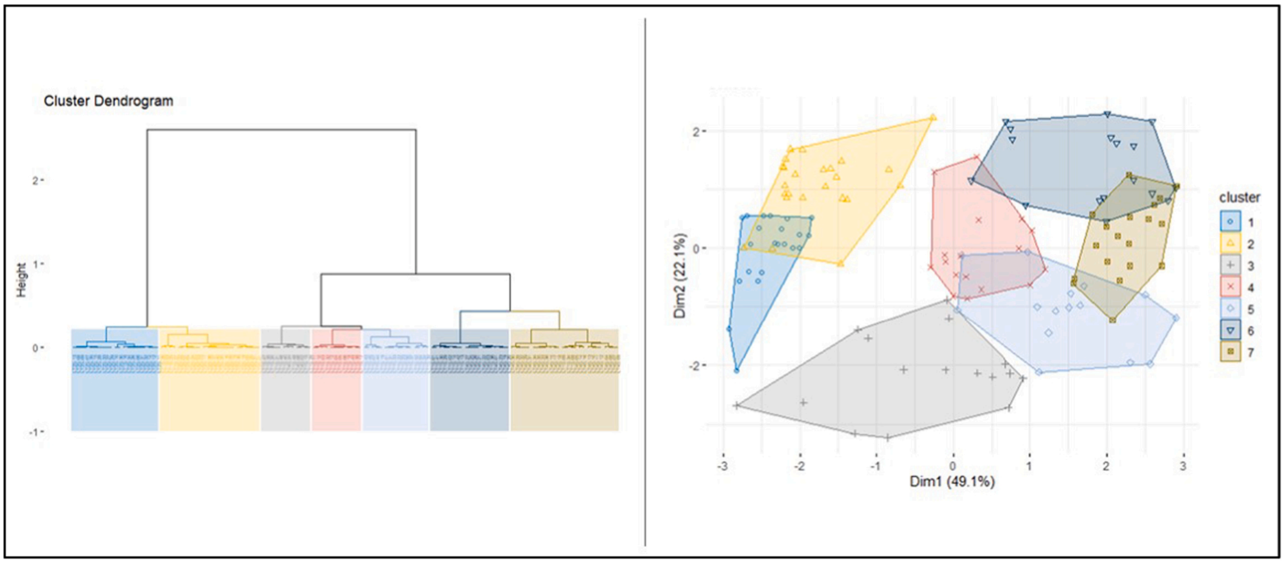

Fig. 4. Hierarchical tree with the subdivision in 7 classes. Different colours represent the 7 different cluster classes.

Table 9
Cross tabulation between the seven hierarchical clusters and the copping systems considered in the different study areas.

	Cl.1	Cl.2	Cl.3	Cl.4	Cl.5	Cl.6	Cl.7
ESH	2	1	16	14	12		9
ESH-1			1	7	5		5
ESH-2		1	6	6	1		4
ESH-3	2		9	1	6		
ITA	20	20					
ITA-3		10					
ITA-2		10					
ITA-1	10						
ITA-4	10						
ESA		3		3	3	17	10
ESA-1		2		3	3		10
ESA-2		1				17	

Where:
ESH-1: Rotations and multicropping under conventional management, ESH-2: Rotations and multicropping under organic management ESH-3 Rotations and multicropping under biodynamic management in the Murcia (ES) region;
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ESA-1: Rotation under conventional tillage, ESA-2, Rotation under no-tillage in the Aragon (ES) region

4.2. Appropriateness of indicators to assess the effect of diversification on cropping systems

All indicators, mainly of measured-effect type, are summarized in a final complex index based on fuzzy logic analysis. This final indicator is built joining several indicators based on agro-environmental and economic aspects of sustainability, and all these indicators are weighted inside the final one based on an expert judgement. For this reason, the methodology is replicable based on the needs of the stakeholders, and results may change depending on the different importance (weight) given to one aspect over another by the users. Other authors (Iocola et al., 2020) constructed an original set of indicators, farm based but more oriented on the cause of the phenomena, that could be sensitive to crop diversification aiming to capture the trade-offs and carry-over effects of diversified cropping systems in ex-ante evaluation.

The main results, as shown in Table 6 and Fig. 2, highlight that the set of indicators used in this study clearly detected the differences among the diversified cropping systems in Mediterranean areas.

The PCA and Hierarchical Cluster Analysis showed that the considered indicators clearly separate the case study data, both geographically (Spain and Italy, with different soil characteristics), and between monoculture and rotation.

We have observed that each indicator had a good performance in discriminating between conventional and diversified crop management. Inside each pilot area single indicators highlight the differences in different way, e.g., the Yield index, SOC index, CDI, and AWC in ESH outlined clearly that biodynamic management had a different effect on soil compared to the other systems; the NI, SOC, and CDI in ITA discriminated the effect of rotation compared with the monocropping systems. In ESA, BD and SOC indicators emphasize better the differences between tillage and no-tillage management.

The general procedure used in this study can be used in different climates than Mediterranean region, taking into account the need to parameterise the weights of the variables, their range of validity and the fuzzy analysis. Hence, for the application of the set of indicators and fuzzy procedure in climatic zones other than Mediterranean, further studies are needed. In the framework of Diverfarming project, further research will be conducted to verify their applicability in other pedoclimatic zones and in other diversified systems.

The choice of using only one year of data for the assessment, have some shortcoming as the effect of annual weather conditions could affect differently the treatments considered. For example Troccoli et al. (2022) reported a better performance in terms of yield in no tillage compared to tillage plots in very dry seasons in ITA. However, in this study we did not consider the single values of the variables, but data are used to build indicators that are based on values ranges evaluated with a fuzzy logic analysis. In this regard, the procedure is independent from the year effect, that is intrinsically inside the range used.

One of the main issues in the use of the indicators included in the ISI is their dependency on data availability, seldom sufficient for the whole assessment reported in this study. This is particularly true in landscape evaluation, where the set of indicators might be lower due the scarce availability of measured variables; in this case the results of assessment must be carefully validated.

The set of indicators was specifically designed to evaluate diversified cropping systems. Its validity outside this scope needs to be validated. Despite its limitations, the proposed set and the fuzzy methodology certainly highlighted how sustainable crop management positively influences soil quality and farm profit and it demonstrated that all the measured indicators are affected by soil management, in accordance with Williams et al. (2020) that showed the impact of soil management on soil health.

5. Conclusions

Diversification showed to be a promising practice to improve soil quality while maintaining an acceptable stability of yields and farm profits. The effect of diversification and low input practice was different in the three areas considered, but all the indicators pointed to an increase of the overall sustainability. The soil fertility, here expressed with SOC and NNI indices, were the most positively affected. The yield presents some reduction as in rotation management in ITA, or remain stable as in ESH and in some case there is an increase as in ESA. The loss of productivity can be overcome by the use of higher income crops in the rotation/diversification, and this can ensure that there are no economic losses in the farm.

In the present study, the set of 7 indicators proposed by DIVERFARMING project assessed comprehensively the outcome of diversification strategies applied in different cropping systems. The indicators showed to be sensitive to crop diversification and capture the effects of diversified cropping systems. The proposed assessment methodology can be expanded to cover other land uses, different crops, and management aspects.

Therefore, both simple and composite indicators calculated with a fuzzy method can be proposed as tool to evaluate the performance of cropping systems, also in the process of co-designing new systems with stakeholders, allowing to display clearly the effect of the alternatives. In our case study, indicators highlight that implementing diversification, reducing soil disturbance and chemical inputs in cropping systems enhanced soil quality. The composite indicators are nowadays essential tools to define local solutions and help the transition of cropping system via diversification strategies across Europe.

CRediT authorship contribution statement

Silvia Vanino: Conceptualization, Methodology, Data curation, Writing – original draft. **Roberta Farina:** Conceptualization, Supervision, Writing – review & editing. **Claudia Di Bene:** Conceptualization, Data curation, Writing – review & editing, **Chiara Piccini**: Conceptualization, Writing – review & editing. **Roman Hüppi:** Conceptualization, Writing – review & editing. **Bruno Pennelli:** Writing – review & editing. **Gianni Fila:** Writing – review & editing. **Virginia Sanchez-Navarro:** Writing – review & editing. **Jorge Alvaro Fuentes:** Writing – review & editing. **Johan Six:** Writing – review & editing. **Raul Zornoza:** Project administration, Writing – review & editing. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Conflicts of Interest

The authors declare no conflict of interest.

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