

A multi-criteria qualitative tool for the sustainability assessment of organic durum wheat-based farming systems designed through a participative process

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Highlights

- *BioDurum_MCA* is an effective tool for sustainability assessment of durum wheat organic Italian production systems.
- Hierarchic structure of the tool reflects the sustainability issues and priorities expressed by involved stakeholders.
- MCA tools can support a holistic evaluation of farm sustainability performances in the frame of post-2020 CAP.

Abstract

The agriculture sustainability assessment is a difficult issue for the coexistence of conflicting objectives and the multidimensionality of the performances. The environmental, economic and

social pillars need to be simultaneously considered in an assessment to evaluate potential synergies and trade-offs of the agricultural processes within and among the attributes of the dimensions in both implemented systems (ex-post analysis) and potential options (ex-ante analysis). Among several sustainability assessment methods, tools based on multi-criteria analysis (MCA) are increasingly adopted in evaluating sustainability in agriculture.

The aim of this work was to present the MCA tool developed in the framework of the BioDurum project for the sustainability assessment of organic farms located in southern Italy and characterised by durum wheat-based crop rotations. The tool was entirely designed through a participatory process and it was realised using the open-source DEXi software that have demonstrated to be particularly suitable for creating qualitative multi-criterial hierarchic models with the engage of stakeholders.

The hierarchic structure of BioDurum_MCA tool was resulted composed by 64 indicators and 45 aggregated attributes articulated in three branches representing the agro-environment, economic, and social sustainability pillars. The articulated structure of the tool reflected the complexity and the sustainability issues and priorities expressed by the involved stakeholders.

The tool was tested in four Italian organic farms presenting different agro-environmental and socio-economic patterns for their ex-post evaluations and in three different ex-ante production systems identified in compliance with the Italian regulation concerning the requirements of the rotations to be implemented in organic farming. The results highlighted the well discriminatory power of the tool. The best overall sustainability scores were reached in both ex-post and ex-ante analysis by the well diversified cereal farming systems with processed products sold through short supply chain mechanisms.

BioDurum_MCA has proved to be a feasible tool to identify strengths and weaknesses of organic durum wheat-based production systems. Its adoption can support the definition of specific interventions for the sector in the Italian Strategic National Plan of the Common Agricultural Policy. Further improvements in the threshold classes of some indicators by using the tool in a wider number of Italian durum wheat based organic farms will increase model sensitivity and reliability of the results. The final version of the tool was released in November 2020 and it is freely available to users (<http://bit.ly/biodurum>).

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See online Appendix for Supplementary tables.

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Introduction

In recent years the European Union (EU) has been strongly committed to increase the sustainability of the European agriculture production sector. Despite controversial views (Kirchmann *et al.*, 2008; Muller *et al.*, 2017), organic farming, not using synthetic fertilisers and pesticides, fostering crop rotations, soil fertility, and biodiversity (Mäder *et al.*, 2002; Reganold and Wachter, 2016) has been called by EU to play a pivotal role in achieving the ambitious goals of the European Green Deal (EC, 2019) and the objectives set out in the Farm to Fork Strategy (EC, 2020). Nevertheless, as with conventional agriculture, very different implementations of the organic agriculture regulation exist, ranging from the input substitution-based methods to an effective deployment of agroecological approaches (Migliorini and Wezel, 2017). Assessing the sustainability of these different organic farming systems is relevant for the implementation of policies and measures addressed to reward farmers for improved sustainability performances and to foster the EU transition towards more sustainable agro-food systems. An effective assessment must be able to face and manage the complexity and the multidimensionality of sustainability (environmental, economic, and social pillars) and the presence of opposing and conflicting issues among and within the pillars (von Wirén-Lehr, 2001; Iocola *et al.*, 2020). The sustainability assessment methods should provide decision making frameworks for the understanding of interactions and resultant trade-offs among dimensions in both existing agriculture systems (ex-post analysis) and potential ex-ante scenarios. This can contribute to help farmers and decision-makers to identify and support suitable practices that most affect the sustainability of the systems, even before their adoption.

A crucial aspect for proper sustainability assessment approaches is also represented by potential users (Carof *et al.*, 2013). Researchers are often more interested in having detailed, not condensed results. On the other hand, policy makers prefer instead to have outcomes in aggregate form (Pacini *et al.*, 2003). While farmers and advisors favour simple methods not requiring expensive measurements or complex parametrisation, but capable however of effectively identifying weaknesses and causes of sustainability lack (von Wirén-Lehr, 2001). Simple and feasible methods allowing to access both elementary data and condensed outcomes are considered *win-win* solutions in case of a combination of potential users.

Ness *et al.* (2007) divided the sustainability assessment methods in three main categories: i) integrated indicators and indices, generally used for retrospective analysis and applied at large national or regional scales; ii) product-related assessment tools analysing flows in connection with the production of a product. These methods are used for both ex-post and prospective analysis, but they are mainly focused on evaluation of environmental impacts. Efforts have been made to create an integrated product-related assessment tool including the three pillars of sustainability, such the life cycle sustainability assessment (Finkbeiner *et al.*, 2010). But this approach is yet considered an infant methodology hampered by computational issues and limitations (Balalay and Halog, 2019); 3) integrated assessment methods including a wide range of tools based on system analysis integrating environmental and socio-economic aspects. These approaches are mainly used for local scale assessments in both ex-post and ex-ante analysis.

Considering the above-mentioned features, the last category contains the most suitable methods for agricultural sustainability assessments, especially for cropping system and farm scale evalu-

ations. Among the integrated assessment approaches, methods based on multi-criteria analysis (MCA) are increasingly adopted in evaluating sustainability in agriculture due to their ability to simultaneously assess contrasting criteria, and analyse complex problems decomposing them into easier elements (Carpani *et al.*, 2012; Craheix *et al.*, 2016). Furthermore, MCA methods are generally organised in decision tree structure that allow users to navigate from a single performance to the aggregated results.

Among MCA approaches, qualitative tools, capable of managing even qualitative data and information, are considered more effective than quantitative methods when a broad diversity of performances arising from different dimensions are included in the evaluation (Sadok *et al.*, 2008; Craheix *et al.*, 2016). Furthermore, the return of the assessment in qualitative terms increases the comprehensibility of the results. This makes the qualitative MCA tool more accessible to a wider range of users than quantitative models do, since qualitative results are considered as natural representations of human views and judgments (Munda, 2005). With the aim of strengthening the sustainability of the Italian organic durum wheat (*Triticum durum* Desf.) production system, a new feasible qualitative MCA tool for the sustainability assessment of organic farms located in Southern Italy was developed in the framework of the BioDurum project (financed by the Italian Ministry of Agriculture - MiPAAF and coordinated by the Council for Agricultural Research and Economics - CREA). The BioDurum_MCA tool was entirely designed through a participatory process by engaging relevant actors of the durum wheat value chain and potential users from the beginning to facilitate the acceptance of outcomes and increase model relevance and impact (Goma *et al.*, 2001; Colomb *et al.*, 2013). The tool was created to be used by different users: i) farmers for self-assessments of their production systems; ii) technicians or advisories for suggesting specific actions to farmers for improving their sustainability; iii) researchers to carry out more complex assessments covering various farms over a wider area. Assessment outcomes must be used to learn lessons that inform decision-making.

The objectives of this work are to present the BioDurum_MCA tool and, specifically, to evaluate its efficacy in managing the complexity and multidimensionality of the sustainability performances related to the organic durum wheat production systems, and the reliability of results in both ex-post and ex-ante evaluations.

Materials and methods

The process carried out to design and build the sustainability MCA assessment tool through stakeholder participation was structured according to the interactive six-step approach proposed by Craheix *et al.* (2015).

Step 1 - Initial analysis and planning

At this early step, relevant actors for the whole durum wheat value chain were identified and involved in the two representative areas of BioDurum project, one in Sicily (SC) and the other across the Basilicata and Puglia (BP) regions. Twenty-six people belonging to different professional categories accepted to participate and they were divided in the following three groups: i) 10 farmers, identified as key stakeholders in each study area (4 in SC and 6 in BP); ii) the internal scientific group composed by 5 researchers (4 in SC and 1 in BP) and 2 model designers to provide reliable sources of scientific knowledge; iii) 11 other pertinent stakeholders that can condition or may be conditioned by the implementation of

durum wheat based agricultural systems (1 agricultural contractor in BP, 3 pasta makers in SC, 5 representatives of producer organisations in BP, and 1 in SC, and 1 representative of the Regional agriculture development agency in BP). Furthermore, an External Scientific Committee (ESC) composed by 4 experts (2 from two Italian Universities and 2 from the CREA Council for Agriculture Research and Economics) was established in a parallel peer-review process to review and validate the outcomes of the different phases of the process (from step 2 to 6). The ESC involvement aimed at strengthening and increasing the credibility of the BioDurum_MCA tool and guaranteeing the transparency of the process.

Step 2 - Selection and hierarchy of the sustainability criteria

Two participatory workshops, held on 22 March 2018 in SC and 27 March 2018 in BP, were organised with the aim to collect actor perspectives and their point of views on aspects and concepts considered relevant for the sustainability assessment. The collected issues were divided directly by the workshop participants into the three agro-environmental, economic and social sustainability pillars. Then the issues were clustered in homogenous themes and sub-theme groups, and organised into a hierarchic tree by model designers.

The root of the hierarchic structure was given by the aggregation of the three sustainability pillars and represented the overall sustainability. Root, themes and subthemes were defined as aggregated attributes because their value is provided by the aggregation of the descendent variables. The resulting tree structure was sent by email to the participants and ESC members with the aim to integrate further missing aspects and for its validation.

During the workshops, the spatial scale of the assessment analysis was also defined. Considering the actors' needs, it was agreed that the model had to be flexible in order to allow the evaluation of different spatial scales covering a field or a group of fields until the whole farm level.

Step 3 - Selection and building of the indicators

Model designers identified the indicators, also called basic attributes or leaves of the tree, to quantify the sustainability sub-themes defined in the hierarchic structure. Factsheets describing the indicators, their formula, input and output data, were prepared and sent to involved researchers, technicians, and ESC in order to collect their feedbacks and suggestions for amendments and changes.

Specifically, the indicators were selected from literature or specifically designed considering: i) their feasibility, to allow their computation with data commonly available in the farm; ii) their scientific value, based on well-acknowledged technical and scientific terms; iii) ability to reflect as much as possible the sustainability-related concepts expressed by the actors during the workshops.

Two types of indicators were included in the tool with the aim to achieve the flexibility required by actors: i) indicators working at field level. These indicators perform their computation using rotation or multi-annual length as temporal scale to consider the carry-over effects of the cropping systems over time and then averaging the results over the number of the evaluated years, to allow the comparison of crop rotations with different lengths. For these indicators computation was performed in each field and the final outcome was obtained by averaging the results of all fields assuming that the contribution of each field is proportional to its surface (Weinstoerffer and Girardin, 2000); ii) indicators that are based on general farm information and they do not need of any spatial

aggregation.

The threshold values of all the calculated indicators for defining their sustainability classes in terms of qualitative scores (*e.g.*, Low, Medium, High) were set considering the assessment context and the expert knowledge of the involved researchers (Table S1 in Appendix).

An Excel file was elaborated to allow users to insert their data and obtain directly the computation of all the indicators. The file was organised in 8 worksheets to be filled in with the required data and information, and 2 worksheets reporting the obtained results of the indicators (one providing the intermediated results of each assessed field, the other supplying the final aggregated outcomes). Furthermore, 4 non-visible worksheets consisting in databases on crops, inputs, work operations and organic durum wheat yields at Italian province scale (from 2009 to 2017, downloaded from the Italian Farm Accountancy Data Network - FADN, <https://www.crea.gov.it/en/web/politiche-e-bioeconomia/-/ricarete-di-informazione-contabile-agricola>) were included and used for the indicator calculation.

Step 4 - Model parameterisation

Two further participatory workshops (on 29 January 2019 in SC and on 15 February 2019 in BP) were carried out to achieve consensus on decision rules and weights based on the perception of sustainability of the local actors. These workshops also provided an opportunity to show the selected indicators to the actors not directly involved in the previous step and to collect their further feedbacks.

In each workshop, participants were divided in three groups (farmers, researchers, other stakeholders). The groups weighted each element of the identified hierarchic tree from the basic attributes to the overall sustainability. Three stickers were provided for each attribute representing a specific sustainability theme or sub-theme. Consequently, groups were allowed to divide the total number of the assigned stickers for each specific aspect of the sustainability among the attributes present in that aspect in relation to their relative importance. The averaged sticker numbers obtained by each element of the tree considering all groups of the two study areas were converted into relative percentages and used as weights in the hierarchic structure.

The hierarchic tree was implemented into the DEXi software (Bohanec, 2013). A macro was realised in the Excel file for importing the sustainability classes obtained by the basic attributes into the DEXi model. The attributes are aggregated by the model up to the most aggregated theme using utility functions (*i.e.*, 'IF-THEN' decision-rules) (Bohanec, 2013; Bohanec *et al.*, 2013) according to their weights. According to Craheix *et al.* (2015), the number of sustainability classes of each tree element was set to increase proceeding from the leaves to the root. This allowed to avoid 'combinatory explosion' of decisional rules in the deepest part of the tree where there were more attributes and to better differentiate results provided by the root and the three sustainability branches. Indeed, the maximum number of classes was reached in agro-environmental, economic and social pillars and in the overall sustainability which were qualified by the following seven progressive modalities: Very Low, Low, Medium Low, Medium, Medium High, High, Very High. Besides the qualitative sustainability scores reported in a table, assessment results were also presented by DEXi as bar, scatter, or radar plots.

Step 5 - Evaluation

A sensitivity analysis was performed to evaluate the model tree

structure and to identify its effects on output results. It was accomplished using the IZIEval tool (<http://wiki.inra.fr/wiki/deximasc/Interface+IZI-EVAL/Accueil>), appositely developed for the analysis of the hierarchical qualitative models built in DEXi (Carpani *et al.*, 2012; Bergez, 2013). Specifically, IZIEval tool was used to: i)

calculate the sensitivity indexes (SI) of basic and aggregated attributes for detecting the effect of the variables on the overall sustainability; ii) perform a Monte Carlo (MC) analysis using 5000 randomly generated samples to obtain the frequency distribution of the values of the overall sustainability and its main components.

Table 1. The four identified farms (F_BP1 and F_BP2 in Basilicata and Puglia Regions, and F_SC1 and F_SC2 in Sicily) with the cropping systems to assess in the ex-post analysis.

Farm	Assessed area (ha)	Number of harvested years	List of crops* for assessed growing seasons	Further inputs
F_BP1	3	3	2016-2017 1. Cover crop (3ha) - Horse bean (<i>Vicia faba</i> L.var. <i>minor</i> Beck) 2017-2018 1. Cover crop (1 ha) - Mix of horse bean (40%) and barley (<i>Hordeum vulgare</i> L.; 60%) followed by sunflower (<i>Helianthus annuus</i> L.) - grain: 1400 kg/ha (0.58 €/kg in LSC); 2. Evolutionary population of Durum wheat (<i>Triticum durum</i> Desf.; 1ha) – grain: 2500 kg/ha (0.385 €/kg in LC); straw: 7600 kg/ha (0.05 €/kg in SSC); 3. Chickpea (<i>Cicer arietinum</i> L.; 1 ha) - grain: 1400 kg/ha (1 €/kg in LSC) 2018-2019 1. Spelt (<i>Triticum spelta</i> L.; 1ha) – grain: 2500 kg/ha (0.41 €/kg in LSC); straw: 5200 kg/ha (0.05 €/kg in SSC); 2. Horse bean (1 ha) – grain: 1800 kg/ha (0.35 €/kg in LSC); 3. Evolutionary population of Durum wheat (1ha) – grain: 2600 kg/ha (0.385 €/kg in LC); straw: 7600 kg/ha (0.05 €/kg in SSC)	<i>Bacillus thuringiensis</i> provided to chickpea (1 kg/ha)
F_BP2	12	3	2016-2017 1. Chickpea (12 ha) - grain: 400 kg/ha (0.6 €/kg in LSC) 2017-2018 1. Cover crop (6 ha) - Mix of vetch (40%) and oats (60%); 2. Spelt (5 ha) – grain: 1000 kg/ha (0.25 €/kg in LSC); 3. Durum wheat (1ha) – grain: 1000 kg/ha (80% at 0.4 €/kg in LSC; 20% processed into semolina and sold at 10€/kg in SSC) 2018-2019 1. Durum wheat (6 ha) – grain: 1000 kg/ha (80% at 0.4 €/kg in LSC; 20% processed into semolina and sold at 10€/kg in SSC); 2. Chickpea (5 ha) - grain: 400 kg/ha (0.6 €/kg in LSC); 3. Cover crop (1 ha) - Mix of vetch (<i>Vicia sativa</i> L.; 40%) and oats (<i>Avena sativa</i> L.; 60%)	Locally produced commercial organic fertiliser applied on (300 kg/ha)
F_SC1	4	4	2015-2016 1. Hemp (<i>Cannabis sativa</i> L.; 2 ha) - grain: 500 kg/ha (processed into oil and sold at 50 €/l in SSC); 2. Durum wheat, local cultivar (2 ha) – grain: 2200 kg/ha (80% at 0.5 €/kg in LSC; 20% processed into semolina and sold at 3.5 €/kg in SSC) 2016-2017 1. Bread wheat (<i>Triticum aestivum</i> L.), local cultivar (2 ha) – grain: 1500 kg/ha (0.6 €/kg in LSC); 2. Hemp (2 ha) - grain: 500 kg/ha (processed into oil and sold at 50 €/l in SSC) 2017-2018 1. Lentil (<i>Lens esculenta</i> Moench.; 2 ha) – grain: 1000 kg/ha (3.5 €/kg in SSC); 2. Chickpea (2 ha) – grain: 750 kg/ha (50% sold at 2 €/kg in LSC; 50% sold at 4 €/kg in SSC) 2018-2019 1. Hemp (2 ha) - grain: 500 kg/ha (processed into oil and sold at 50 €/l in SSC); 2. Durum wheat, local cultivar (2 ha) – grain: 2500 kg/ha (80% at 0.5 €/kg in LSC; 30% processed into semolina and sold at 3.5 €/kg in SSC)	On-farm produced compost applied on all crops (using the same dose of 1750 kg/ha); Ox blood fertiliser (25 kg/ha) applied on Durum wheat in 2019
F_SC2	14	4	2015-2016 1. Durum wheat (14 ha) – grain: 1200 kg/ha (0.52 €/kg in SSC); straw: 3000 kg/ha (0.02 €/kg in SSC) 2016-2017 1. Sulla clover (<i>Hedysarum coronarium</i> L.; 14 ha) – whole plant: 1500 kg/ha (0.15 €/kg in SSC) 2017-2018 1. Sulla clover (14 ha) – grain: 400 kg/ha (100% re-used by farmer) 2018-2019 1. Durum wheat (14 ha) – grain: 1400 kg/ha (0.52 €/kg in SSC)	

*Yields, selling prices, and supply chain mechanisms (LSC, long supply chain; SSC, short supply chain) for cash crops are reported.

The evaluation of model outputs was performed using both ex-post and ex-ante assessments. For the ex-post analysis, the farms with durum wheat-based systems to evaluate were selected among those belonging to the farmers which participated to the development of the tool and presenting different agro-environmental and socio-economic patterns. The identified 4 farms (F_BP1 and F_BP2 in BP, F_SC1 and F_SC2 in SC) and the assessed cropping systems are described in Table 1. Required data were collected by interviews carried out by local technicians and the involved researchers.

In the ex-ante analysis, 3 different systems were identified by researchers in compliance with the Italian regulation concerning the requirements of the rotations to be implemented in organic farming (DM 3757/2020) and simulated using collected data and operations management carried out in F_BP1. They were: i) the three-year rotation R1 (DW-F-Fa-DW) characterised by the following crop sequence: durum wheat (DW), horse bean as cover crop (F; *Vicia faba* L. var. *minor* Beck) succeeded by six months fallow (Fa), and durum wheat; ii) the three-year rotation R2 (DW-FB-C-DW) including the following crops: durum wheat, mix of horse bean (60%) and broccoli rabe (*Brassica rapa* L. subsp. *sylvestris* L. Janch. var. *esculenta* Hort) (40%) as cover crop (FB), chickpea (C; *Cicer arietinum* L.), and durum wheat; iii) the four-year rotation R3 (DW-FB-C-DW-F-Fa) characterised by the same crop sequence of R2 but with the addition of F and Fa.

Considering the ex-ante systems, some changes with respect to the data reported in F_BP1 were made only in DW. Indeed, the evolutionary population was replaced by a single cultivar as practiced by most of the organic farms in the area. Furthermore, yield of the first durum wheat in the crop sequence of rotations R1 and R2 was reduced of 20% because of the presumably lower soil nitrogen availability.

Due to the COVID-19 sanitary emergency that did not allow to hold the foreseen workshops for the validation step in presence, the obtained ex-post and ex-ante assessment results were presented and discussed with researchers and technicians through various web meetings. Subsequently outcomes were shown to a wider audience including farmers who participated at the process in a further web conference held on 22 October 2020.

Step 6 - Model transfer

The BioDurum_MCA tool (composed by the integration of the Excel file and the DEXi tree model) was accompanied by a detailed user manual and all files were sent on 20 April 2020 to the ESC, researchers and technicians for a first testing of the prototype. Suggestions and improvements were integrated in the tool and a second prototype was presented and used in a training web workshop held on 21 October 2020 where farmers and additional technicians who did not take part at the process were invited.

The final version of the tool was released in November 2020 and it is freely available to users (<http://bit.ly/biodurum>). All documents are in Italian language.

Results

Hierarchic tree

The resulting hierarchic structure of BioDurum_MCA was composed by 109 attributes (64 indicators and 45 aggregated variables) articulated in three branches representing the agro-environment (EnvSust, weight=44%), economic (EconSust, weight=36%),

and social (SocSust, weight=20%) sustainability pillars (Table 2).

EnvSust was characterised by a total of three macro themes: i) Natural resources management (NatMan; weight=47%) where sub-themes related to Soil (Erosion - Ero; Soil organic carbon - SOC; Soil Structure - SoilStr), Biodiversity - Biodiv (Genetic diversity - GenDiv; Specific diversity - SpeDiv; Habitat - Hab), and Water (Impact on water quantity - WatQt; Impact on water quality - WatQl) were included. A total of 20 indicators were identified in this area of the hierarchic tree (Table 2). A brief description of indicators, formulas and required inputs are reported in Table S1 in the Appendix; ii) Crop practices (Crop_pract; weight=38%) with the sub-themes related to Fertilisations - Fert (Nitrogen fertilisation - N; Phosphorus fertilisation - P), Crop protection management - ProtMan (Preventive techniques - PrevT; Curative management - CurM), and Energy (Energy consumption - EnC; Energy autonomy - EnAut) were considered together with 12 indicators; iii) Environmental attention (EnvAtt, weight=15%) which was characterised by the sub-themes Climate change management - CC and Waste management - Waste and containing three indicators.

The economic sustainability pillar was represented by three main themes: i) Economic viability (EVit, weight=50%) including the sub-themes related to the Economic Result - ERes (in terms of the economic efficiency - Eff calculated as a ratio between revenues and costs; durum wheat yield WY, and yield stability computed with a coefficient of variation CV. Both WY and CV were compared with values obtained with data from FADN in the province where the farms are located), Independency - Ind (from public aid and inputs), and Multifunctionality- Mult with a total of 8 indicators; ii) Product valorisation (Val, weight=25%) where sub-themes related to Product quality - PQ (both technological and sanitary quality) and Certification (Cert) were considered with an aggregation of 3 basic indicators; iii) Markets (Mk, weight=25%) characterised by Selling arrangements - SAR (in terms of selling channels and farmer-buyer agreements), Short value chains - SVC (with regard to percentage of products sold to and economic relevance of local chains), and Contribution to the development of new supply chain (NCD) with a number of 5 indicators.

Lastly, social sustainability dimension was composed by the following three themes: i) Work (weight=24%) containing the sub-themes Contribution to employment-CEmp (in terms of annual hours worked), Work contracts - TCont (considering the temporary employees and disadvantaged workers), and Workplace safety (Wsaf) and including 4 indicators; ii) Human capital (HC, weight=47%) composed by the subthemes Cooperation - Coop (with reference to activities and machinery managed in collaboration with other farmers, and participation in consortia), and Innovation - Inn (with regard to propensity, related to age and degree of both farmer and employees, training, equipment updating, and engagement of the farm in research projects) and including a total of 7 indicators; iii) Territory development (TDev, weight=29%) composed directly by two basic indicators. They were the Communication and awareness-raising (Com), related to activities carried out by farm (e.g., open days, on-farm learning activities, etc.) to increase community awareness about sustainability, and the Value of the landscape (LandV) which the farm gives back to society weighing up its positive and negative elements.

Sensitivity analysis

The results of the SI calculation obtained for the three pillars EnvSust, EconSust, and SocSust (located at the depth 2 of the hierarchic tree), their main themes (depth 3), and the most influential basic attributes (SI \geq 0.008) for each main theme are reported in

Table 2. Hierarchic structure and attributes of BioDurum_MCA. Depth gives the position of the attributes in the hierarchic tree. Acronyms are provided in parentheses after the names of the attributes. Type reports if an attribute derives from an aggregation through an utility function (A - aggregated attribute in bold) or it is an indicator (B - basic attribute). Weight provides the aggregation weight (0-100). Lastly, Class reports the number of the classes of each attribute (e.g., 7 classes=Very Low, Low, Medium Low, Medium, Medium High, High, Very High).

Depth	Attribute (Acronym)	Type	Weight	Class
1	Overall sustainability (Ovsust)	A	100	7
2	└─ Agroenvironment sustainability (Envsust)	A	44	7
3	└─└─ Natural resources management (NatMan)	A	47	5
4	└─└─└─ Soil	A	39	4
5	└─└─└─└─ Erosion (Ero)	A	34	4
6	└─└─└─└─└─% Soil cover (Cov)	B	62	4
6	└─└─└─└─└─Slope (Slp)	B	38	3
5	└─└─└─└─ Soil organic carbon (SOC)	A	36	4
6	└─└─└─└─└─Carbon Input (CInp)	B	52	4
6	└─└─└─└─└─Tillage (Till)	B	48	4
5	└─└─└─└─ Soil Structure (SoilStr)	A	30	3
6	└─└─└─└─└─Presence of soil structure problems (StrPr)	B	67	3
6	└─└─└─└─└─ Control of soil structure (StrCtr)	A	33	3
7	└─└─└─└─└─└─Machinery traffic management (MacTraf)	B	33	3
7	└─└─└─└─└─└─Strategies for soil structure regeneration (StrReg)	B	67	3
4	└─└─ Biodiversity (Biodiv)	A	39	3
5	└─└─└─ Genetic diversity (GenDiv)	A	29	3
6	└─└─└─└─Cultivar diversity (Cult)	B	40	3
6	└─└─└─└─Local cultivars (LocCult)	B	60	4
5	└─└─└─ Specific diversity (SpeDiv)	A	42	3
6	└─└─└─└─ Space and temporal specific diversity (STDiv)	A	83	3
7	└─└─└─└─└─Total numbers of crops in a rotation (Nrot)	B	38	3
7	└─└─└─└─└─Simpson index in time and space (Simp)	B	43	3
7	└─└─└─└─└─Intercropping (InterCrop)	B	19	3
6	└─└─└─└─└─Percentage of legume crops (Leg)	B	17	3
5	└─└─└─ Habitat (Hab)	A	29	3
6	└─└─└─└─Ecological Focus Areas (EFA)	B	67	3
6	└─└─└─└─Fields size (Size)	B	33	3
4	└─└─ Water (Wat)	A	22	3
5	└─└─└─ Impact on water quantity (WatQt)	A	50	3
6	└─└─└─└─Water volume (Watvol)	B	33	3
6	└─└─└─└─Water reuse (WatReuse)	B	33	3
6	└─└─└─└─Micro-irrigation (Microirr)	B	33	3
5	└─└─└─ Impact on water quality (WatQI)	A	50	3
6	└─└─└─└─N leaching risk (NRisk)	B	67	3
6	└─└─└─└─P run-off risk (PRisk)	B	33	3
3	└─└─ Crop practices (Crop pract)	A	38	5
4	└─└─└─ Fertilisations (Fert)	A	57	3
5	└─└─└─└─ Nitrogen fertilisation (N)	A	70	3
6	└─└─└─└─└─N balance (NBal)	B	57	3
6	└─└─└─└─└─Fraction of used N from farm (NFarm)	B	43	3
5	└─└─└─└─ Phosphorus fertilisation (P)	A	30	5
6	└─└─└─└─└─P balance (PBal)	B	40	3
6	└─└─└─└─└─Recycling of P from crop residues (PReuse)	B	40	4
6	└─└─└─└─└─Non-renewable P (PNRw)	B	20	3
4	└─└─└─ Crop protection management (ProtMan)	A	21	4
5	└─└─└─└─Preventive techniques (PrevI)	B	52	4
5	└─└─└─└─ Curative management (CurM)	A	48	4
6	└─└─└─└─└─Curative techniques (CurI)	B	67	3
6	└─└─└─└─└─Amount of used Copper (Cu)	B	33	3
4	└─└─ Energy	A	22	3
5	└─└─└─ Energy consumption (EnC)	A	43	4
6	└─└─└─└─Direct energy consumption (DiEnC)	B	56	4

Continued on next page.

Table 2. Continued from previous page.

6		└ Indirect energy consumption (InDiEnC)	B	44	4
5		└ Energy autonomy (EnAut)	A	57	3
6		└ Renewable energy production (EnRw)	B	67	2
6		└ Reuse of energy inputs on energy consumption (EnReuse)	B	33	3
3		└ Environmental attention (EnvAtt)	A	15	5
4		└ Climate change management (CC)	A	64	3
5		└ Adaptation strategies (CCAd)	B	67	3
5		└ Mitigation strategies (CCMit)	B	33	3
4		└ Waste management (Waste)	B	36	3
2		└ Economic sustainability (EconSust)	A	36	7
3		└ Economic viability (EViT)	A	50	5
4		└ Economic Result (ERes)	A	41	3
5		└ Economic Efficiency (EEf)	B	50	3
5		└ Wheat yield (WY)	B	30	3
5		└ Yield stability (CV)	B	20	3
4		└ Independency (Ind)	A	41	3
5		└ Independency from public aid (Aid)	B	33	3
5		└ Independency from Inputs (Input)	A	67	3
6		└ Seeds input (SInp)	B	40	3
6		└ N fertilisers input (NInp)	B	40	3
6		└ Other inputs (OInp)	B	20	3
4		└ Multifunctionality (Mult)	B	18	3
3		└ Product valorisation (Val)	A	25	3
4		└ Product quality (PQ)	A	67	3
5		└ Technological quality (QTE)	B	50	3
5		└ Sanitary quality (QSA)	B	50	3
4		└ Certifications (Cert)	B	33	3
3		└ Markets (Mk)	A	25	5
4		└ Selling arrangements (SAr)	A	41	3
5		└ Number of selling channels (NSC)	B	67	3
5		└ Type of agreement between farmer and buyers (TAgr)	B	33	3
4		└ Short value chains (SVC)	A	41	3
5		└ Percentage of products sold through short value chains (SCPr)	B	50	3
5		└ Economic importance of short value chains (SCEc)	B	50	3
4		└ Contribution to new supply chain development (NCD)	B	18	3
2		└ Social sustainability (SocSust)	A	20	7
3		└ Work	A	24	5
4		└ Contribution to employment (CEmp)	B	44	3
4		└ Work contracts (WCon)	A	22	3
5		└ Share of temporary employees (TempW)	B	53	3
5		└ Social inclusion of disadvantaged workers (SocW)	B	47	2
4		└ Workplace safety (Wsaf)	B	33	3
3		└ Human capital (HC)	A	47	5
4		└ Cooperation (Coop)	A	45	3
5		└ Activities managed jointly with other farmers (JAct)	B	32	3
5		└ Machinery shared with other farmers (SMac)	B	32	2
5		└ Participation in consortia (ConP)	B	36	3
4		└ Innovation (Inn)	A	55	3
5		└ Propensity for innovation (PrInn)	B	35	3
5		└ Updating (Upd)	A	35	3
6		└ Training	B	67	3
6		└ Machinery and equipment (Mac)	B	33	3
5		└ Research and Experimentation (Ric)	B	30	2
3		└ Territory development (TDev)	A	29	3
4		└ Communication and awareness-raising (Com)	B	50	3
4		└ Value of the landscape (LandV)	B	50	3

Figure 1. The variables showing the longest bars have the highest influence on the overall sustainability. The most influencing sustainability domain was Envsust (SI=0.442), followed by EconSust (SI=0.315) and SocSust (SI=0.123). Within each pillar, the main contributing variables were Crop_pract (SI=0.21) with its basic attribute NBal (SI=0.089) for Envsust, Evit (SI=0.169) with the EEf indicator (SI=0.038) for EconSust, and HC (SI=0.075) with its input variables Consr and Prop (both SI=0.016) for SocSust.

The frequency distributions of the 5000 simulated outputs obtained with MC analysis for the overall sustainability and the three pillars are shown in Table 3. More than 68% of the results were concentrated in the Medium Low and Medium classes in all the four attributes of the hierarchic tree.

Ex-post assessment

Considering the overall sustainability, F_B1 and F_SC1 were evaluated as the most sustainable farms (respectively High and Medium High), followed by F_BP2 (Medium Low) and lastly by F_SC2 (Low) (Table 4).

The agro-environmental pillar showed the same outcomes. More detailed results (Table 4 and Table S5 in Appendix) indicated that the best score reached by F_B1 for Envsust was due to Soil (mainly for the carbon input CInp attribute, with the highest calculated value of 0.302 t C ha⁻¹y⁻¹) and ProtMan (with the highest score of 4.56 for the applied preventive techniques). A good per-

formance in Fert (principally obtained for a well score in the ratio between nutrient inputs and outputs for both NBal=0.80 and PBal=0.70) contributed to increase the sustainability for F_SC1. By contrast, the agro-environmental sustainability of both F_B2 and F_SC2 were instead reduced by a worse performance in nutrient management. F_SC2 results were further aggravated by a low score in biodiversity. High score obtained by F_BP2 in EnvAtt as a consequence of the implementation of some climate change mitigation strategies (i.e., minimum tillage), slightly increased the sustainability of this farm.

Regarding the economic dimension, F_BP1 and F_SC1 obtained better scores (both Medium High), than F_SC2 (Medium) and F_BP2 (Medium Low). F_BP1 and F_SC1 presented their major strengths in ERes compared to the other farms. Indeed, both F_BP1 and F_SC1 reached a high performance in all indicators included in the aggregated attribute ERes: the economic efficiency Eff (3.04 in F_BP1 and 5.34 in F_SC1), durum wheat yield WY (0.83 in F_BP1 and 0.87 in F_SC1) and yield stability CV (0.25 in F_BP1 and 0.69 in F_SC1). In F_BP2, the worst performance showed for the attribute Ind, caused by a high incidence of subsidies on a low gross margin, contributed to reduce its economic sustainability.

For the social dimension, the F_BP1 presented the best evaluation (Medium High), while the other farms showed a Medium Low score. In F_BP1, the presence of a great number of main and

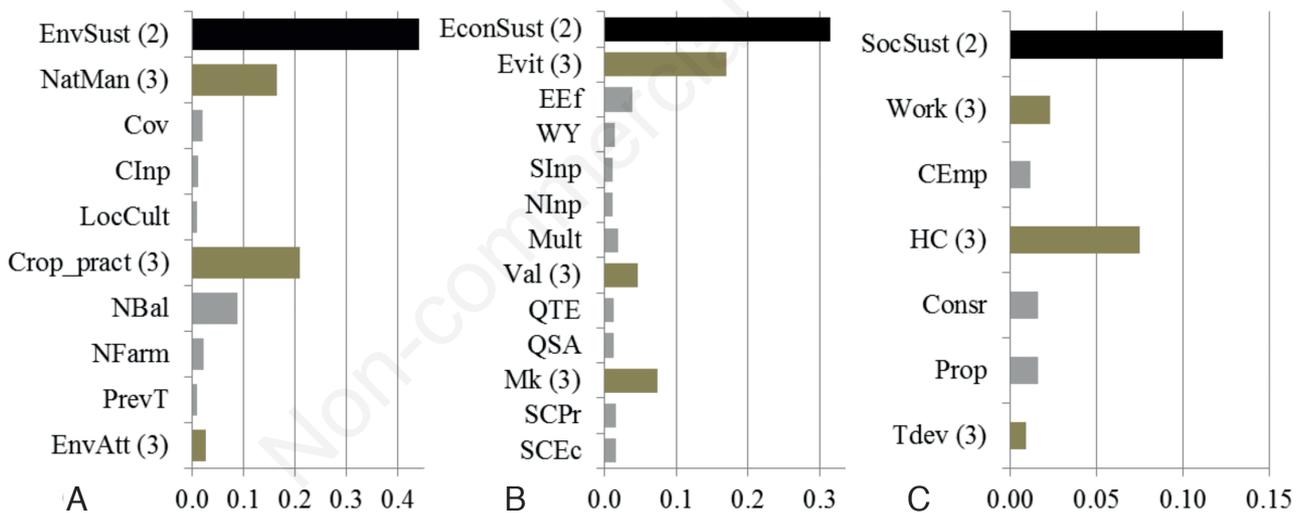


Figure 1. Values of the sensitivity index - SI (X-axis) obtained for the three sustainability pillars of the hierarchic tree of BioDurum_MCA tool: (A) Agro-environmental - Envsust; (B) Economic - EconSust; (C) Social sustainability - SocSust, their main themes, and the most influential basic attributes (SI≥0.008). The SI bar is black for variables at the depth 2 of the hierarchic tree (2), light brown for depth 3 (3), and grey for basic attributes. Y gives the abbreviations of the name of the variables (see Table 2) followed by their depth (in brackets) in case of aggregate attributes.

Table 3. Relative frequency distributions of the results of 5000 simulations among the seven classes (Very Low, Low, Medium Low, Medium, Medium High, High, Very High) for the overall sustainability (Ovsust), the agro-environmental (Envsust), economic (EconSust), and social (SocSust) pillars of BioDurum_MCA.

	Very Low	Low	Medium Low	Medium	Medium High	High	Very High
Ovsust	0.01	0.12	0.46	0.37	0.05	0.00	0.00
Envsust	0.02	0.10	0.31	0.46	0.09	0.03	0.00
EconSust	0.02	0.08	0.32	0.45	0.11	0.01	0.01
SocSust	0.03	0.13	0.32	0.36	0.14	0.03	0.00

cover crops in field, and crop practices and tillage carried out with care and precision had a positive impact on the contribution to local employment ($CEmp=6.21\text{hour ha}^{-1} \text{y}^{-1}$). Furthermore, the job placement of disadvantaged people carried out by F_BP1 (considered in the Wcon) and the period training courses followed by the farmer and his employees (accounted in Inn) contributed to increase the social sustainability of this farm.

Ex-ante assessment

The overall sustainability scores of the assessed ex-ante systems were Medium for R1(DW-F-Fa-DW) and High for R3 (DW-FB-C-DW-F-Fa), with R2 (DW-FB-C-DW) positioned in the middle (Medium High) (Figure 2A).

The increase in agro-environmental sustainability hypothesized in the definition of the ex-ante systems was confirmed by the

assessment results obtained for this pillar (Figure 2B). Indeed, R1 reported the worst performance (Medium Low), while R2 and R3 showed a better score, respectively Medium High and High.

The good performance reached by the latter two systems for Envsust were specifically caused by (Figure 2C): better scores in Soil for higher values of CInp attribute; a greater biodiversity due to more crops in the rotations (Nrot) and to a better spatial and temporal diversity calculated by the modified Simpson index - Simp; higher scores for the applied preventive techniques thanks to the introduction of Brassica in cover cropping. Conversely, Brassica as cover crop contributed to limit the R2 performance for NBal because of the reduced nitrogen input. Instead, the additional legume cover crop present in R3 allowed not to reduce the score of this rotation for NBal.

Considering the economic sustainability pillar, R3 reached a

Table 4. Sustainability assessment results obtained with BioDurum_MCA for farms F_BP1 and F_BP2 in Basilicata and Puglia regions, and F_SC1 and F_SC2 in Sicily. The outcomes refer to the overall sustainability, the three pillars, the main themes and sub-themes (until depth 4) of the hierarchic tree. The abbreviations of the name of the variables (see Table 2) are given followed by their depth (in brackets).

	F BP1	F BP2	F SC1	F SC2
Ovsust (1)	High	Medium Low	Medium High	Low
└─Envsust (2)	High	Medium Low	Medium High	Low
└─└─NatMan (3)	High	Medium	Medium	Low
└─└─└─Soil (4)	Very High	Medium	Medium	Medium
└─└─└─Biodiv (4)	Medium	Medium	Medium	Low
└─└─└─Wat (4)	Medium	High	High	High
└─└─└─Crop pract (3)	High	Low	Very High	Low
└─└─└─Fert (4)	Medium	Low	High	Low
└─└─└─ProtMan (4)	Very High	High	High	High
└─└─└─Energy (4)	High	High	High	High
└─└─└─EnvAtt (3)	Medium	High	Medium	Medium
└─└─└─CC (4)	Medium	High	Medium	Medium
└─└─└─Waste (4)	Medium	Medium	High	Medium
└─EconSust (2)	Medium High	Medium Low	Medium High	Medium
└─└─Evit (3)	High	Low	High	Medium
└─└─└─ERes (4)	High	Low	High	Medium
└─└─└─Ind (4)	High	Medium	High	High
└─└─└─Mult (4)	Low	Low	Low	Low
└─└─└─Val (3)	Medium	Medium	Medium	Medium
└─└─└─PQ (4)	High	High	High	High
└─└─└─Cert (4)	Low	Low	Low	Low
└─└─└─Mk (3)	Medium	Medium	Medium	Medium
└─└─└─SAr (4)	Medium	Medium	Medium	Medium
└─└─└─SVC (4)	Medium	Medium	Medium	High
└─└─└─NCD (4)	Medium	Low	Medium	Low
└─SocSust (2)	Medium High	Medium Low	Medium Low	Medium Low
└─└─Work (3)	Very High	Medium	Medium	Medium
└─└─└─CEmp (4)	High	Low	Medium	Low
└─└─└─Wcon (4)	High	Medium	Low	Medium
└─└─└─Wsaf (4)	High	High	High	High
└─└─└─HC (3)	Medium	Low	Low	Low
└─└─└─Coop (4)	Low	Low	Low	Low
└─└─└─Inn (4)	High	Medium	Medium	Medium
└─└─└─TDev (3)	Medium	Medium	High	Medium
└─└─└─Com (4)	Medium	Medium	High	Low
└─└─└─LandV (4)	Medium	Medium	Medium	Medium

Medium High performance followed by R2 and R1 (both Medium) (Figure 2B). The aggregated attribute ERes with its three indicators Eef, WY, and CV was the principal responsible for the different outcomes (Figure 2C). Indeed, R3 reported better values for durum wheat yield and yield stability than the other systems. Regarding the economic efficiency Eef, all ex-ante systems reached the score High, although R2 achieved the best value in quantitative terms.

Lastly, as the three systems presented the same range of performance in all variables of the hierarchical tree for the social sustainability pillar, they obtained the same score in SocSust (Medium High).

Discussion

Strengths and weakness of the hierarchical structure and its attributes

The articulated structure of BioDurum_MCA reflects the complexity and the sustainability issues expressed by the involved stakeholders. The holistic approach carried out in designing the tool, avoiding any predefined sustainability criterion dictated by the scientific community, allowed involved actors to reflect about sustainability and define their objectives, values, and priorities.

The engagement and interactions among various stakeholders in the development of an assessment tool are essential to create a learning environment where actors learn from each other and settle their divergences (Bond and Morrison-Saunders, 2013; Schindler *et al.*, 2015). Stakeholders engagement is also very relevant in ensuring ownership and acceptance of the evaluation results, thus encouraging the implementation of solutions to improve the sustainability of the assessed systems (Goma *et al.*, 2001; Colomb *et al.*, 2013; Cosyns *et al.*, 2013).

Although with a predominance of themes of the agro-environmental dimension, all the three sustainability pillars were well

expressed and developed in the hierarchic structure of the tool. Their aggregation and the simultaneous assessment of the sustainability dimensions facilitated users to better understand direct and indirect links among variables within and across pillars and to evaluate trade-offs. Indeed, despite the large number of variables, the choice of the software DEXi, embedded in BioDurum_MCA, with its simple aggregation approach, makes possible to trace the effects of the change of an attribute value up to the three pillars and the overall sustainability. This raises the awareness of the implications that an action has on the whole outcome (Sadok *et al.*, 2009).

The principal challenge faced in the realisation of the tool was to set a proper trade-off between the contrasting demand for feasible analysis and accurate results. As farms are often characterised by data availability constraints, indicators to quantify the concepts expressed by the actors were mainly identified and built to better exploit information and data commonly present in a farm. By combining together simple measurable data, qualitative information, and using literature values for data gaps, BioDurum_MCA was fully skilled to achieve the feasibility requirement. Although capable of identifying strengths and weaknesses in the sustainability of a farm, however, in many cases, the indicators of the tool give estimations and potential risks related to variables instead of providing their exact measures, especially for the agro-environmental pillar.

The sustainability issues and priorities expressed by actors were fully respected in the hierarchical structure thanks to the weights assigned to each attribute. The main priorities were maintained even after the aggregation of the attributes in the hierarchical structure as highlighted by SI results.

Considering the agro-environmental dimension, soil and biodiversity in natural resources management were considered very relevant by actors in terms of sustainability. Among variables belonging to Soil, the presence of soil organic carbon represents a key characteristic of healthy soils (Brandão and Canals, 2013). However, further efforts have to be done to increase the accuracy of the soil organic carbon estimation that is quantified by CInp indicator. If data are not available, crop aboveground residues left in field are calculated from observed crop yields using harvest

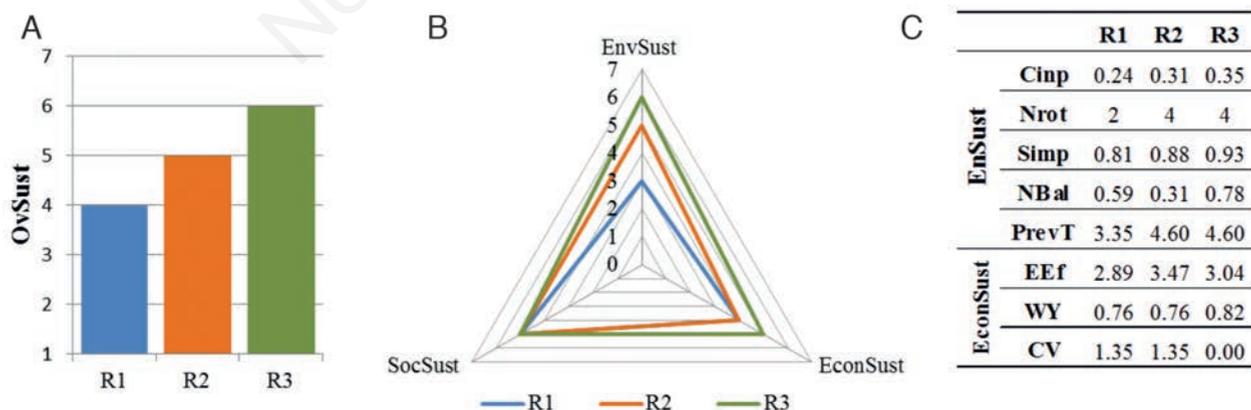


Figure 2. Sustainability assessment results obtained with BioDurum_MCA for the ex-ante systems R1 (DW-F-Fa-DW) in light blue, R2 (DW-FB-C-DW) in orange, and R3 (DW-FB-C-DW-F-Fa) in green. Performances for (A) the overall sustainability - Ovsust, and for (B) the agro-environmental - Envsust, economic - EconSust), and social - SocSust pillars of the hierarchic tree where 1: Very Low; 2: Low; 3: Medium Low; 4: Medium; 5: Medium High; 6: High; 7: Very High; (C) Quantitative results of the main indicators determining the different sustainability performances for the three assessed systems.

indexes (HI) reported in Salmoral and Garrido (2015). HI values for durum wheat were instead set to 0.25 and 0.40 respectively for ancient and modern varieties according to De Vita *et al.* (2007). Considering the cash crops for which data related to aboveground residues were collected in farms, observed HI values were lower (<-20%) than those reported in Salmoral and Garrido (2015), which are most commonly obtained under high nitrogen input management. Indeed, organic systems are often affected by limited macronutrient availability, especially when environmental and soil conditions reduce mineralisation process of organic inputs (Lammerts van Bueren *et al.*, 2011). A very low soil nutrient availability likely also occurs in farms assessed in this study, in particular in those characterised by bad performance in nutrient management and poor soil structure. Furthermore, as underlined by Lammerts van Bueren *et al.* (2011), organic production is further aggravated by the use of crop varieties mainly bred for the conventional high input sector which lack important traits needed to achieve high yields under poor nutrient availability contest. Further adjustments are therefore almost certainly required for the harvest indexes of the crops reported in the database of the tool to be more in line with organic farming values.

The three fundamental categories of biodiversity (ecosystem, species and genetic diversity) were included in the tool because these three levels are not independent but interact each other enhancing the agroecosystem resilience (Noss, 1990; Yachi and Loreau, 1999). Indicators were specially designed to capture both spatial and temporal biodiversity of the cropping systems. Indeed, as confirmed by farmers and several authors (Kremen *et al.*, 2012; Tamburini *et al.*, 2020), well diversified and complex systems with cover crops, long rotations articulated in various rotational areas are able to control damage caused by pest and disease and reduce weed populations. Biodiversity represents therefore a relevant key strategy used in organic production to overcome the ban on the use of synthetic fertilisers and pesticides. Furthermore, the use of locally adapted varieties was strongly seen by actors as an additional strategy to enhance the resilience of the system and reduce genetic erosion, especially in Sicily where actors aimed at a reevaluation the Sicilian durum wheat landraces (Palumbo *et al.*, 2003; Palumbo *et al.*, 2008; Sciacca *et al.*, 2014; Sciacca *et al.*, 2018).

Aspects related to water utilisation were also wisely considered. Even if most of the organic cereal production systems are rainfed, water withdrawal was included in the tool to take into account the context of climate change and not to limit the creation of potential ex-ante scenarios.

Regarding crop practices, an adequate management of N and P resources was considered by actors a fundamental priority to the maintenance of soil fertility and crop productivity over the long term, especially in organic systems characterised by nitrogen scarcity which limits yields of non-leguminous crop (Watson *et al.* 2002). On the contrary, at the beginning of the process, Energy issues received relatively little attention than other variables. Attributes on direct and indirect energy consumptions were proposed by researchers in a revision phase of the tree structure and accepted by other actors.

A further debate arose among stakeholders on the use of copper in crop protection management. According to the researchers, copper amount was not relevant in organic arable cropping systems. Producers and technicians insisted on its inclusion as farmers often use copper-based treatments on cereal seeds to combat fungal diseases rather than focusing on preventive techniques (*i.e.*, resistant varieties, crop biostimulants, *etc.*).

Climate change was widely mentioned in both study areas and seen as a priority challenge. Climate change indicators are actually

based on a sum of mitigation and adaptation strategies cited by the involved actors to which a score was assigned. Above all, stakeholders considered very relevant the use of wheat cultivar mixtures or heterogeneous populations, able to evolve and adapt over time thanks to the natural selection of the environment (evolutionary breeding) for facing the changing climatic conditions (Weedon and Finckh, 2019; Bocci *et al.*, 2020). These simple indicators could be changed in the future with complementary basic attributes assessing greenhouse gases emissions from modelling approach. A satellite tree could be implemented in the tool as those adopted by other MCA models (Sadok *et al.*, 2009; Colomb *et al.*, 2013) in order to give users the choice of the basic attributes to select on the basis of the evaluation context and data available.

In the economic pillar, all actors considered the economic profitability very relevant for the sustainability of a farm. The economic return of organic cereal-based farms varies greatly depending on crop rotation and product transformation. Since it was very difficult to define agreed classes of sustainability related to profitability due to farmers' subjective well-being, economic efficiency based on the ratio between revenue and operational costs (Vilain *et al.*, 2008) was selected and used in the tool. Gross margin is also calculated in the tool and returned to users without entering into the sustainability assessment. The drawback of this choice is that a farm can be evaluated more economically sustainable than another if it has a better performance in efficiency even if the profitability can be lower.

Profitability is also closely related to obtained yields and, in a long term, to a properly yield stability. In BioDurum MCA, these two indicators are entirely focused on durum wheat, but of course their performances are strongly influenced by rotations in which this crop is inserted. The ESC suggested to modify the first version of these indicators defining the sustainability classes according to a ratio between values calculated in the farms with those obtained with FADN data in the same geographical area of reference. All the variability of FADN database (2009-2017) is actually exploited, but, in the future, indicators could be improved by allowing user to choose, if available, only FADN data related to the years subject to the assessment.

In the macro-theme Product valorisation, ESC also suggested to change the proposed indicator selected from French literature (Craheix *et al.*, 2011) for the evaluation of the technological quality of durum wheat. Indeed, as the previous indicator was based on a farmer's risk perception of not reaching standard quality required by the sector/market, it was considered too subjective. The new QTE proposed by ESC assesses whether the minimum values of some quantitative parameters for grains (total impurities, grain test weight, thousand kernel grain weight, loss of vitreous aspect), easily calculable by farmers, are reached. Grain protein content was not included in the assessed parameters because it was considered a data not readily available in farms. Furthermore, according to actors and data available in this study for some involved farms, the minimum values of protein percentage required by markets are generally achieved in an organic production system, despite the low nitrogen fertilisation rate, because of the low yields and the use of old durum wheat varieties characterised by higher protein content (Giunta *et al.*, 2020). Quality of farm products is further taken into account by the indicator Certification. The use of standards, certification, and labelling was evaluated by actors both as a way supporting consumers to make purchasing decisions and as a marketing strategy than can contribute to improve the income of farmers. Short supply chains mechanisms are also strongly endorsed by stakeholders because they guarantee higher revenues, direct contact between producers and consumers, and fairer trade

(Migliorini and Scaltriti, 2012).

The social dimension has always received less attention by scientific research than environmental and economic pillars in the performance evaluation of an agriculture production system (Bacon *et al.*, 2012; Gaviglio *et al.*, 2016). Although this dimension received less weight than the others in the hierarchical structure of the tool, the multi stakeholder engagement approach allowed avoiding underestimating this pillar. In particular, actors of BP region contributed most to enriching the social sustainability tree branch.

The maintenance of a sustainable level of employment was considered a priority. According to the involved actors, well-diversified and complex cereal-based systems generate a high and steady workload throughout the years which requires permanent workforce, thus reducing the use of short-term contracts and the trap of illegal labour.

Cooperation and innovation represent relevant instruments for the sustainability enhancement of a farm and important aspects for human development in rural areas (Vilain *et al.*, 2008; Gaviglio *et al.*, 2016). Cooperation, shared activities and machinery with other neighbouring farms are also relevant factors indicated by the involved actors and assessed by the tool. Furthermore, according to stakeholders, training and knowledge exchanges play a key role for innovation in agriculture sector as also highlighted by Vilain *et al.* (2008). Farmers are also called up to raise the awareness of consumers and civil society in order to actively contributing to a sustainable territorial development. Indeed, the implication of a farm in events such as open days, educational and recreational activities, increases the knowledge and understanding of the agro-food system by citizens which often conduct to a positive change of their behaviour (Kneafsey *et al.*, 2013).

Assessment results

The Monte Carlo analysis showed that both very positive and very negative assessment results of overall sustainability and its three pillars are the most difficult to achieve. These findings are also highlighted by the evaluation carried out in this study where no farm was scored in the extreme sustainability classes.

The Ex-post analysis highlighted that good soil-fertility management practices based on-farm resources (cover crops in F_BP1 and on-farm organic compost in F_SC1) ensured a sustainable agronomic viability. Moreover, cover crop introduction in F_BP1 contributed to further strengthen the sustainability of this farm for a better soil health, a decreased soil erosion risk, and an improved control of weeds and pathogens (Langdale *et al.*, 1991; Creamer *et al.*, 1996). F_SC2, being characterised by no cover crops and a low spatial and temporal biodiversity, resulted the less performing farm. A wider diffusion of cover crops in organic farming is still limited due to some critical factors such as the suitable selection of plant species or mixtures to adopt, the identification of proper seeding and termination time, and the additional expenses due to seed and their management (Canali *et al.*, 2015). However, cover crops can contribute to reduce costs related to fertilisers, weed and disease control and, most importantly, they constitute a long-term investment in soil resources, thus ensuring a long-term crop productivity.

The good soil fertility management allowed to obtain a good productivity of durum wheat in F_BP1 and F_SC1 thus ensuring performing economic results. In addition, high revenues obtained for processed products, the use of short supply chain mechanisms, the introduction of innovative crops scarcely present in the area (such as hemp for F_SC1 and the evolutionary population of durum wheat in F_BP1) largely contributed to improve the eco-

nomical sustainability of these two farms. In F_BP2, despite the high revenues obtained from the sale of processed products sold through short supply chains, the very low crop productivity due to a poor soil fertility and a problematic soil structure, did not allow to achieve a good economic sustainability performance. Lastly, the greater attention to social aspects presented by F_BP1 and their inclusion in the assessment has further positively distinguished this farm from the others.

The ex-post sustainability assessments were in line with the expectations of technicians and researchers who collected the data and who profoundly knew the realities of these farms. Profiling existing systems is very useful to identify strong points to be conserved and weaknesses to improve (Colomb, 2013; Iocola *et al.*, 2020). Other than for the validation of the tool, this was also the secondary aim of this first assessment. Indeed, outcomes were used to discuss with involved farmers and identify strategies to increase their sustainability, mainly based on a better exploitation of the beneficial effects of cover crops in a rotation. These strategies could be assessed with the tool through an ex-ante analysis in order to evaluate the resulting potential trade-offs before the real implementation in the farms.

The discriminatory power of BioDurum_MCA was also highlighted in the evaluation of the three ex-ante systems identified in compliance with the Decree of the Italian of the Ministry for Agriculture on organic farming rotations (DM 3757/2020). The three assessed rotations were scored by the tool in accordance with their hypothesized increasing agro-environmental sustainability level. Like in the ex-post analysis, the most diversified system R3, characterised by a higher presence of agro-ecological service crops and a well spatial and temporal biodiversity, performed better than the others. However, even if this system has also shown a good performance in the economic dimension reaching a high score for the economic efficiency, a more in-depth analysis shows that its economic attractiveness could be reduced. Indeed, considering gross margin, value in R3 only increased by 31% respect to the simplified system R1, while R2 reached an increase of 73% due to the greater number of cash crops than cover crops in this rotation.

Furthermore, the increasing diversification of the ex-ante systems did not affect unexpectedly the performance related to the direct energy consumption variable, where all the three systems reached the same qualitative Medium score. Correctly choosing the thresholds between qualitative classes of an attribute and properly defining the number of its classes to avoid *combinatory explosion* of rules in the aggregation with other variables are the major difficulties and challenges in this type of modelling for not losing sensitivity (Bohanec *et al.*, 2008; Craheix *et al.*, 2015). The threshold values of the indicators were defined by expert knowledge and considering the assessment context and data observed in the ex-post farming systems, but, most likely they need to be further validated using data coming from a much larger and statistically significant number of organic farms to increase the reliability of results.

Conclusions

BioDurum_MCA has proved to be an effective and feasible tool to manage and assess the complexity of the sustainability performances related to durum wheat organic production of southern Italian farming systems. The factors that influence organic farming agro-environmental, economic, and social sustainability pillars are explored and taken into account by the tool valuing the indications and ratings expressed by the different actors engaged since the

beginning of the design process. By considering the diversity of viewpoints, the adopted approach has allowed to combine both scientific and local knowledge, not neglecting ethical and cultural issues relevant for the local actors.

The discriminatory power of the tool was highlighted both in ex-post and ex-ante analysis. The results of the assessments carried out in this study pointed out that well diversified cereal cropping systems with agro-ecological service crops contributed most to enhance biodiversity, improve soil nitrogen fertility, and better manage weed and diseases. Once fully operational, these diversified systems simultaneously ensure satisfactory and stable crop productivity that, coupled with processed products sold through short supply chain mechanisms, fosters economic viability and the overall farm sustainability. However, further improvements of the tool as the increase of its sensitivity and reliability, might be obtained by fine tuning the threshold classes of some of the indicators included in the model. This objective is achievable through additional testing, applying the tool to a wider number of Italian durum wheat based organic farms and mobilising supplementary and multidisciplinary technical and scientific expertise.

Data availability at cropping system and farm scale has often revealed to be a relevant bottleneck for the implementation of sustainability assessment tools that require wide datasets from different dimensions. Thanks to the mobilisation of relevant actors activated through the participatory approach, data acquisition, proper selection of indicators and feasibility of their computation in operational condition were achieved in BioDurum_MCA tool, ensuring an intentional balancing between applicability and scientific quality.

In order to allow the exploitation of the full potential of sustainability assessing tools at farm and cropping system levels, as proposed in 'Eu Farm to Fork' strategy, the expansion of the aims and the structure of FADN to become Farm Sustainability Data Networks should be convincingly pursued. This will guarantee to encompass the survey and collection of farm data other than those merely related to the accounting purposes, thus including information associated with the environmental and social dimensions of farming activities. The potential of the tool, especially in the agro-environmental assessment, should be also enriched by leveraging data from digital agriculture (*i.e.*, remote sensing images, drones and sensors) which will become increasingly available in the near future.

BioDurum_MCA has demonstrated to be a valid and feasible tool to identify strengths and weaknesses of organic durum wheat production systems which can be encouraged or deterred through proper policies and measures and rewarding the assessed farms for an improvement in their sustainability performances over time.

The pursuit of a sustainable agriculture is much more explicit than before in the post-2020 Common Agricultural Policy (CAP). The adoption of the tool in organic durum wheat-based production systems can support a more holistic approach in the definition of specific and effective interventions for the sector in the Italian Strategic National Plan of the CAP.

As most of BioDurum indicators already takes into account in the computation not only durum wheat but all crops of the assessed systems, future research efforts could focus on expanding the tool to assess the sustainability performance of different organic production systems in order to provide insights for recommendations and interventions for all organic Italian agriculture sector.

References

- Bacon CM, Getz C, Kraus S, Montenegro M, Holland K, 2012. The social dimensions of sustainability and change in diversified farming systems. *Ecol. Soc.* 17:41.
- Balanay R, Halog A, 2019. Tools for circular economy: review and some potential applications for the Philippine textile industry. In *Circular Economy in Textiles and Apparel*. Woodhead Publishing, pp. 49-75.
- Bergez JE, 2013. Using a genetic algorithm to define worst-best and best-worst options of a DEXi-type model: application to the MASC model of cropping-system sustainability. *Comput. Electron. Agric.* 90:93-8.
- Bocci R, Bussi B, Petitti M, Franciolini R, Altavilla V, Galluzzi G, Di Luzio P, Migliorini P, Spagnolo S, Floriddia R, Li Rosi G, Petacciato M, Battezzato V, Albino A, Faggio G, Arcostanzo C, Ceccarelli S, 2020. Yield, yield stability and farmers' preferences of evolutionary populations of bread wheat: A dynamic solution to climate change. *Eur. J. Agron.* 121:126156.
- Bohanec M, 2013. DEXi: Program for multi-criteria decision making, user's manual, Version 4.0. IJS Report DP-113401134011340, Jožef Stefan Institute, Ljubljana. Available from: <http://kt.ijs.si/MarkoBohanec/pub/DEXiManual400DEXiManual400DEXiManual400.pdf>
- Bohanec M, Messéan M, Scatasta S, Angevin F, Griffiths B, Krogh PH, Znidarsic M, Dzeroski S, 2008. A qualitative multi-attribute model for economic and ecological assessment of genetically modified crops. *Ecol. Model* 215:247-61.
- Bohanec M, Rajkovič V, Bratko I, Zupan B, Žnidaršič M, 2013. DEX methodology: three decades of qualitative multi-attribute modelling. *Informatica* 37:49-54.
- Bond A, Morrison-Saunders A, 2013. Better learning. In: Bond A, Morrison-Saunders A, Howitt R (Eds.), *Sustainability assessment. Pluralism, practise and progress*. Routledge. Taylor & Francis Group, New York, pp 216-230.
- Brandão M, Canals LM, 2013. Global characterisation factors to assess land use impacts on biotic production. *Int. J. Life Cycle Assess.* 18:1243-52.
- Canali S, Diacono M, Campanelli G, Montemurro F, 2015. Organic no-till with roller crimpers: Agro-ecosystem services and applications in organic Mediterranean vegetable productions. *Sustain. Agric. Res.* 4:70.
- Carof M, Colomb B, Aveline A, 2013. A guide for choosing the most appropriate method for multi-criteria assessment of agricultural systems according to decision-makers' expectations. *Agric. Syst.* 115:51-62.
- Carpani M, Bergez JE, Monod H, 2012. Sensitivity analysis of a hierarchical qualitative model for sustainability assessment of cropping systems. *Environ. Model Softw.* 27:15-22.
- Colomb B, Carof M, Aveline A, Bergez JE, 2013. Stockless organic farming: strengths and weaknesses evidenced by a multicriteria sustainability assessment model. *Agron. Sustain. Dev.* 33:593-608.
- Cosyns H, Damme PV, Wulf RD, 2013. Who views what? Impact assessment through the eyes of farmers, development organisation staff and researchers. *Int. J. Sustain. Dev. World Ecol.* 20:287-301.
- Craheix D, Angevin F, Bergez JE, Bockstaller C, Colomb B, Guichard L, Reau R, Doré T, 2011. MASC 2.0, un outil d'évaluation multicritère pour estimer la contribution des systèmes de culture au développement durable. *Innov. Agron.* 20:35-48.
- Craheix D, Angevin, F, Doré T, de Tourdonnet S, 2016. Using a

- multicriteria assessment model to evaluate the sustainability of conservation agriculture at the cropping system level in France. *Eur. J. Agron.* 76:75-86.
- Craheix D, Bergez JE, Angevin F, Bockstaller C, Bohanec M, Colomb B, Doré T, Fortino G, Guichard L, Pelzer E, Méssean A, Reau R, Sadok W, 2015. Guidelines to design models assessing agricultural sustainability, based upon feedbacks from the DEXi decision support system. *Agron. Sustain. Dev.* 35:1431-47.
- Creamer NG, Bennett MA, Stinner BR, Cardina J, Regnier EE, 1996. Mechanisms of weed suppression in cover crop-based production systems. *HortSci.* 31:410-3.
- De Vita P, Nicosia OLD, Nigro F, Platani C, Riefolo C, Di Fonzo N, Cattivelli L, 2007. Breeding progress in morpho-physiological, agronomical and qualitative traits of durum wheat cultivars released in Italy during the 20th century. *Eur. J. Agron.* 26:39-53.
- DM 3757, 2020. Disposizioni per l'attuazione dei regolamenti (CE) n. 834/2007 e n. 889/2008 e loro successive modifiche e integrazioni, relativi alla produzione biologica e all'etichettatura dei prodotti biologici. Ministerial Decree 3757/2020 of the Ministry of Agricultural, Food and Forestry Policies (Mipaff), 9th April 2020, Official Journal of Italian Republic [in Italian].
- EC, 2020. A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system (Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions). European Commission, Brussels. COM (2020) 381 final.
- EC, 2019. The European Green Deal (Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions). European Commission, Brussels. COM(2019) 640 final.
- Finkbeiner M, Schau EM, Lehmann A, Traverso M, 2010. Towards life cycle sustainability assessment. *Sustainability* 2:3309-22.
- Gaviglio A, Bertocchi M, Marescotti ME, Demartini E, Pirani A, 2016. The social pillar of sustainability: A quantitative approach at the farm level. *Agric. Food Econ.* 4:15.
- Giunta F, Bassu S, Mefleh M, Motzo R, 2020. Is the technological quality of old durum wheat cultivars superior to that of modern ones when exposed to moderately high temperatures during grain filling? *Foods* 9:778.
- Goma HC, Rahim K, Nangendo G, Riley J, Stein A, 2001. Participatory studies for agro-ecosystem evaluation. *Agric. Ecosyst. Environ.* 87:179-90.
- Kirchmann H, Bergström L, Katterer T, Andrén O, Andersson R, 2008. Can organic crop production feed the world? In: Kirchmann H, Bergström L (Eds.), *Organic crop production-ambitions and limitations*. Springer, Berlin, pp 39-72.
- Kneafsey M, Venn L, Schmutz U, Balázs B, Trenchard L, Eydenwood T, Bos E, Sutton G, Blackett M, 2013. Short food supply chains and local food systems in the EU. A state of play of their socio-economic characteristics. *JRC Sci. Policy Rep.* 123-9.
- Kremen C, Iles A, Bacon C, 2012. Diversified farming systems: An agroecological, systems-based alternative to modern industrial agriculture. *Ecol. Soc.* 17:44.
- Iocola I, Angevin F, Bockstaller C, Catarino R, Curran M, Méssean A., Schader C, Stilmant D, Van Stappen F, Vanhove P5, Ahnemann H, Berthomier J, Colombo L, Dara Guccione G, Mérot E, Palumbo M, Virzi N, Canali S, 2020. An actor-oriented multi-criteria assessment framework to support a transition towards sustainable agricultural systems based on crop diversification. *Sustainability* 12:5434.
- Lammerts van Bueren ET, Jones SS, Tamm L, Murphy KM, Myers JR, Leifert C, Messmer MM, 2011. The need to breed crop varieties suitable for organic farming using wheat, tomato and broccoli as examples. *NJAS Wageningen J. Life Sci.* 58:193-205.
- Langdale GW, Blevins RL, Karlen DL, McCool KK, Nearing MA, Skidmore EL, Thomas AW, Tyler DD, Williams JR, 1991. Cover crop effects on soil erosion by wind and water. In: W.L. Hargrove (Ed.), *Cover crops for clean water*. Soil and Water Conservation Society. Ankeny, IA, pp 15-22.
- Mäder P, Fliessbach A, Dubois D, Gunst L, Fried P, Niggli U, 2002. Soil fertility and biodiversity in organic farming. *Science* 296:1694-7.
- Migliorini P, Scaltriti B, 2012. Evaluation of sustainability of the farms in the Agricultural Park of South Milan and their production chain. *New Medit.* 11:53-6.
- Migliorini P, Wezel A, 2017. Converging and diverging principles and practices of organic agriculture regulations and agroecology. A review. *Agron. Sustain. Dev.* 37:63.
- Muller A, Schader C, El-Hage Scialabba N, Brüggemann J, Isensee A, Erb KH, Smith P, Klocke P, Leiber F, Stolze M, Niggli U, 2017. Strategies for feeding the world more sustainably with organic agriculture. *Nat Commun* 8:1290.
- Munda G, 2005. Multiple criteria decision analysis and sustainable development. In: S. Greco (Ed.), *Multiple criteria decision analysis: state of the art surveys*. Springer, New York, NY, USA, pp. 953-986.
- Ness B, Urbel-Piirsalu E, Anderberg S, Olsson L, 2007. Categorising tools for sustainability assessment. *Ecol. Econ.* 60:498-508.
- Noss RF, 1990. Indicators for monitoring biodiversity: a hierarchical approach. *Conserv. Biol.* 4:355-64.
- Palumbo M, Blangiforti S, Cambrea M, Gallo G, Licciardello S, Spina A, 2008. Sicilian durum wheat landraces for production of traditional breads. pp 132-132 in *Proc. Int. Durum Wheat Symposium "From Seed to Pasta: The Durum Wheat Chain"*, Bologna, Italy.
- Palumbo M, Sciacca F, Virzi N, Boggini G, 2003. Breadmaking quality of Sicilian durum wheat landraces. pp 77-81 in *Proc. 2° International workshop: "Durum wheat and pasta quality: recent achievements and new trends"*, Roma, Italy.
- Pacini C, Wossink A, Giesen G, Vazzana C, Huirne R, 2003. Evaluation of sustainability of organic, integrated and conventional farming systems: a farm and field-scale analysis. *Agric. Ecosyst. Environ.* 95:273-88.
- Reganold JP, Wachter JM, 2016. Organic agriculture in the twenty-first century. *Nat. Plants* 2:1-8.
- Sadok W, Angevin F, Bergez JE, Bockstaller C, Colomb B, Guichard L, Reau R, Doré T, 2008. Ex ante assessment of the sustainability of alternative cropping systems: implications for using multi-criteria decision-aid methods. A review. *Agron. Sustain. Dev.* 28:163-74.
- Sadok W, Angevin F, Bergez JE, Bockstaller C, Colomb B, Guichard L, Reau R, Méssean A, Doré T, 2009. MASC, a qualitative multi-attribute decision model for ex ante assessment of the sustainability of cropping systems. *Agron. Sustain. Dev.* 29:447-61.
- Salmoral G, Garrido A, 2015. The Common Agricultural Policy as a driver of water quality changes: the case of the Guadalquivir River Basin (southern Spain). *Bio-based Appl. Econ. J.* 4:103-23.
- Schindler J, Graef F, König HJ, 2015. Methods to assess farming sustainability in developing countries. A review. *Agronomy for*

- Sustainable Development, Springer Verlag/EDP Sciences/INRA, 35 (3), pp.1043-1057.
- Sciaccia F, Allegra M, Licciardello S, Rocuzzo G, Torrìs B, Virzì N, Brambilla M, Romano E, Palumbo M, 2018. Potential use of Sicilian landraces in biofortification of modern durum wheat varieties: evaluation of caryopsis micronutrient concentrations. *Cereal Res. Commun.* 46:124-34.
- Sciaccia F, Cambrea M, Licciardello S, Pesce A, Romano E, Spina A, Virzì N, Palumbo M, 2014. Evolution of durum wheat: from Sicilian landraces to improved varieties. *Opt. Médit. Ser. A* 110:139-45.
- Tamburini G, Bommarco R, Wanger TC, Kremen C, van der Heijden, MG, Liebman M, Hallin S, 2020. Agricultural diversification promotes multiple ecosystem services without compromising yield. *Sci. Adv.* 6:eaba1715.
- Vilain L, Boisset K, Girardin P, Guillaumin A, Mouchet C, Viaux P, Zahm F, 2008. La méthode IDEA: Indicateurs de durabilité des exploitations agricoles - Guide d'utilisation, 3eme édition, Editions Educagri, Dijon, 159 p.
- von Wirén-Lehr S, 2001. Sustainability in agriculture- an evaluation of principal goal-oriented concepts to close the gap between theory and practice. *Agric. Ecosyst. Environ.* 84:115-29.
- Yachi S, Loreau M, 1999. Biodiversity and ecosystem productivity in a fluctuating environment: The insurance hypothesis. *Proceedings of the National Academy of Sciences* 96:1463-8.
- Watson CA, Atkinson D, Gosling P, Jackson LR, Rayns FW, 2002. Managing soil fertility in organic farming systems. *Soil Use Manag.* 18:239-47.
- Weedon OD, Finckh MR, 2019. Heterogeneous winter wheat populations differ in yield stability depending on their genetic background and management system. *Sustainability* 11:6172.
- Weinstoerffer J, Girardin P, 2000. Assessment of the contribution of land use pattern and intensity to landscape quality: use of a landscape indicator. *Ecol. Model.* 130:95-109.

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