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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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 hierarchical models with the engagement of stakeholders.

The hierarchic structure of BioDurum_MCA tool was resulted composed by 64 indicators and 45 aggregated attributes articulating 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).
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 Wezell, 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 Wienen-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 Wienen-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 (Balanay 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 evaluations. 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 (Carpiani 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 advisors 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 subthemes 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/-/ricerche-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 <br> 1. Cover crop (3 ha) - Horse bean (Vicia faba L. var. minor Beck) <br> 2017-2018 <br> 1. Cover crop (1 ha) - Mix of horse bean (40%) and barley (Hordeum vulgare L.; 60%) followed by sunflower (Helianthus annuus L.) - grain: 1400 kg/ha (0.58 €/kg in LSC); <br> 2. Evolutionary population of Durum wheat (Triticum durum Desf; 1 ha) - grain: 2500 kg/ha (0.385 €/kg in LC); straw: 7000 kg/ha (0.05 €/kg in SSC); <br> 3. Chickpea (Cicer arietinum L; 1 ha) - grain: 1400 kg/ha (1 €/kg in LSC) | Bacillus thuringiensis provided to chickpea (1 kg/ha) |
| F_BP2 | 4                  | 4                          | 2016-2017 <br> 1. Chickpea (12 ha) - grain: 400 kg/ha (0.6 €/kg in LSC) <br> 2017-2018 <br> 1. Cover crop (6 ha) - Mix of vetch (40%) and oats (60%); <br> 2. Spelt (5 ha) - grain: 1000 kg/ha (0.25 €/kg in LSC); <br> 3. Durum wheat (1 ha) - grain: 1000 kg/ha (80% at 0.4 €/kg in LSC; 20% processed into semolina and sold at 10€/kg in SSC) | Locally produced commercial organic fertiliser applied on (300 kg/ha) |
| F_SC1 | 4                  | 4                          | 2015-2016 <br> 1. Hemp (Cannabis sativa L; 2 ha) - grain: 500 kg/ha (processed into oil and sold at 50 €/l in SSC); <br> 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) <br> 2016-2017 <br> 1. Bread wheat (Triticum aestivum L), local cultivar (2 ha) - grain: 1500 kg/ha (0.6 €/kg in LSC); <br> 2. Hemp (2 ha) - grain: 500 kg/ha (processed into oil and sold at 50 €/l in SSC) | On-farm produced compost applied on all crops (using the same dose of 1750 kg/ha); Oxi blood fertiliser (25 kg/ha) applied on Durum wheat in 2019 |
| F_SC2 | 4                  | 4                          | 2015-2016 <br> 1. Durum wheat (14 ha) - grain: 1200 kg/ha (0.52 €/kg in SSC); straw: 3000 kg/ha (0.02 €/kg in SSC) <br> 2016-2017 <br> 1. Sulla clover (Hedysarum coronarium L; 14 ha) - whole plant: 1500 kg/ha (0.15 €/kg in SSC) <br> 2017-2018 <br> 1. Sulla clover (14 ha) - grain: 400 kg/ha (100% re-used by farmer) | |

*Yield, 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-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-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 - WatQ; Impact on water quality - WatQI) 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 (CropP; 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 (E Vit, 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 computed with values obtained with data from FADN in the province where the farms are located), Independence - 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 (Wsal) 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 propensit, 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 ≥ 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 (Clnp)                                     | B    | 52     | 4     |
| 6     | Tillage (Tll)                                           | B    | 48     | 4     |
| 5     | Soil Structure (SolStr)                                | 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     |
| 5     | 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     | Interseeding (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 (WatQi)                       | A    | 50     | 3     |
| 6     | Water volume (Watvol)                                  | B    | 33     | 3     |
| 6     | Water reuse (WatReuse)                                 | B    | 33     | 3     |
| 6     | Micro-irrigation (Microir)                              | 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 (PrevT)                          | B    | 52     | 4     |
| 5     | Curative management (CurM)                             | A    | 48     | 4     |
| 6     | Curative techniques (CurT)                             | 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     |

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Table 2. Continued from previous page.

|   | Economic sustainability (EconSust) |   |   |
|---|-----------------------------------|---|---|
| 6 | Indirect energy consumption (IndEnC) | B | 44 | 3 |
| 5 | Energy autonomy (EnAut) | A | 57 | 3 |
| 6 | Renewable energy production (EnRwp) | B | 67 | 3 |
| 6 | Reuse of energy inputs on energy consumption (EnReuse) | B | 33 | 3 |
| 3 | Environmental attention (EnvAtt) | A | 15 | 3 |
| 4 | Climate change management (CC) | A | 64 | 3 |
| 4 | Adaptation strategies (CCAd) | B | 67 | 3 |
| 5 | Mitigation strategies (CCMit) | B | 33 | 3 |
| 4 | Waste management (Waste) | B | 36 | 3 |

|   | Economic viability (EV) |   |   |
|---|------------------------|---|---|
| 2 | Economic viability (EV) | A | 50 | 3 |
| 4 | Economic Result (ERes) | A | 41 | 3 |
| 5 | Economic Efficiency (EEf) | B | 50 | 3 |
| 2 | Wheat yield (WY) | B | 30 | 3 |
| 5 | Yield stability (CV) | B | 20 | 3 |
| 4 | Independence (Ind) | A | 41 | 3 |
| 5 | Independence from public aid (Aid) | B | 33 | 3 |
| 5 | Independence from Inputs (Input) | A | 67 | 3 |
| 6 | Seeds input (Slnp) | B | 40 | 3 |
| 6 | N fertilisers input (Nlnp) | B | 40 | 3 |
| 6 | Other inputs (Olnp) | B | 20 | 3 |
| 4 | Multifunctionality (Multi) | 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 | 3 |
| 4 | Selling arrangements (SAr) | A | 41 | 3 |
| 5 | Number of selling channels (NSC) | B | 67 | 3 |
| 5 | Type of agreement between farmer and buyers (TAgri) | 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 |

|   | Social sustainability (SocSust) |   |   |
|---|-------------------------------|---|---|
| 2 | Work | A | 24 | 3 |
| 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 (Wsafe) | 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 (SMach) | 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 (Mach) | B | 33 | 3 |
| 5 | Research and Experimentation (ResC) | 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 C(Inp attribute, with the highest calculated value of 0.302 t C ha⁻¹ y⁻¹) and ProtMan (with the highest score of 4.56 for the applied preventive techniques). A good performance 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 ERs compared to the other farms. Indeed, both F_BP1 and F_SC1 reached a high performance in all indicators included in the aggregated attribute ERs: the economic efficiency Ef (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
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 hour ha⁻¹ 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 ClnP 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

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**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         | Medium         |
| Wat (4)        | Medium         | High           | High           | High           |
| Crop_pract (3) | High           | Low            | Very High      | Low            |
| Fert (4)       | Low            | High           | High           | Low            |
| ProtMan (4)    | Very High      | High           | High           | High           |
| Energy (4)     | High           | High           | High           | High           |
| FevAt (3)      | Medium         | High           | Medium         | Medium         |
| CC (4)         | Medium         | High           | Medium         | Medium         |
| Waste (4)      | Medium         | Medium         | High           | Medium         |
| **EcosSust (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           |
| Multi (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         |
| SAT (4)        | Medium         | Medium         | Medium         | Medium         |
| SVC (4)        | 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         |
| Wsa (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 hierarchical 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
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 context. 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 revaluation the Sicilian durum wheat landraces (Palumbo et al., 2003; Palumbo et al., 2008; Sciaccia et al., 2014; Sciaccia 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
The socio-economic 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 economic 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 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 combinatorial explosion of rules in the aggregation with other variables are the major difficulties and challenges in this type of modelling for not losing sensitivity (Bohiance 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.

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