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RESEARCH ARTICLE

A multifunctional life cycle assessment of durum wheat cropping systems

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Abstract

Agricultural systems strongly impact ecosystems by driving terrestrial degradation, water depletion, and climate change. The Life Cycle Assessment allows for comprehensive analyses of the environmental impacts of food production. Nonetheless, its application still faces challenges due to cropping systems' increased complexity and multifunctionality. Past research has emphasized the need for more holistic approaches to consider dynamic crop interactions and diverse functions of cropping systems, beyond just meeting the demand for foods and feeds. In this context, this study applied an alternative combined and multifunctional modelling approach to compare the environmental performances of two durum wheat cropping systems. The latter differed in crop rotation schedules, farming methods, tillage techniques, and genotypes grown (including both modern and old ones). Novel methodological choices were adopted in this study, aiming at best representing the complexity and peculiarities of these systems, by considering crop rotation effects and reflecting the main durum wheat stakeholders' perspectives. The results showed that the organic low-input landrace-growing system (Case 1) had considerably lower environmental impacts than the conventional high-input one (Case 2), regardless of the functional unit. The environmental hotspots were the increased land occupation and the bare fallow for Case 1 and Case 2, respectively. At the endpoint level, the most affected impact categories for both the systems of analysis were land use, fine particulate matter formation, global warming (human health), and human non-carcinogenic toxicity. Also, the midpoint analysis pointed out important differences in terms of other assessed impact categories, with Case 1 better performing for the majority of them. The identified improvement solutions include the following: the enhancement of the yield performances and the optimization of nitrogen provision from the leguminous crop for Case1, the shift toward a more efficient rotational scheme, the reduction of the use of external inputs, and the avoidance of unnecessary soil tillage operations for Case 2.

Keywords Environmental sustainability · Organic · Conventional · Crop rotation · Landraces · Quality

1 Introduction

The global food system faces the enormous challenge of producing nutritious food, while adapting to climate change, protecting natural resources, and conserving biodiversity (Capone et al. 2014). Agricultural production is largely documented in the literature to dominate many of the environmental impacts of food systems, mainly due to land use, terrestrial degradation, water depletion, and greenhouse gas (GHG) emissions (Poore and Nemecek 2018). It has been estimated that the global agricultural and livestock production sectors utilize 40% of the total land, account for 70% of freshwater use, and are responsible for 23% of anthropogenic GHG emissions (IPCC 2019a; Niles et al. 2018). Therefore, designing sustainable and efficient cropping systems has become critical to enhancing and maintaining ecosystem services and achieving several of the UN sustainable development goals (SDGs) (e.g., SDG#2 Zero Hunger, 3, 6, SDG#13 Climate Action, and SDG#15 Life on Land) (Bouma et al. 2019). Life Cycle Assessment (LCA) is one of the tools that can be used for environmental assessments of farming systems,

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to identify the hotspots and the improvement potentials, thereby contributing to sustainable food production systems (Meier et al. 2015). However, there are still many unsolved methodological challenges in the application of LCA in the agri-food sector, such as the difficulty of accurately modelling cropping systems because of their inherent high complexity, variability, and multifunctionality (Berardy et al. 2020; Notarnicola et al. 2017; Goglio et al. 2018). Indeed, different crops alternate within a crop rotation, and each of them influences the productive and environmental performances of the next one, based on its agricultural management practices and specific ability to affect soil quality. For instance, possible interactions across crops and over the years were documented to be the nutrient carryover, the reduction of the use of agricultural operation needs, and the different intensity and timing of farming activities (Brankatschk and Finkbeiner 2015; Peter et al. 2017). However, most of those interactions, also called crop rotation (CR) effects, are dynamic, site-dependent, and hard to quantify within LCAs (Peter et al. 2017). Consequently, they have been scarcely considered in LCAs of agricultural systems, and no consensus has been reached within the scientific community for their accounting (Goglio et al. 2018). The majority of CR effects pose methodological issues in defining spatial and temporal boundaries and choosing the allocation rules (Goglio et al. 2018). Different modelling approaches have been adopted so far, depending on whether a system or a product LCA is developed. In the former case, the cropping system approach has been recommended while, in the latter, allocation and combined approaches have been tested, though none of them was found to be fully exhaustive and accurate (Goglio et al. 2018). Besides being complex and variable, cropping systems typically provide multiple services that go beyond the primary function of meeting the demand for foods and feeds. They are essential, in fact, also for generating income, maintaining agrobiodiversity, preserving rural areas, and ensuring nutritional quality and security (Green et al. 2020; Grassauer et al. 2021). To best capture this multifunctionality, it has been recommended to select more than one functional-unit (FU) options and to determine to which extent their choice and adoption influence the environmental results (Martínez-Blanco et al. 2011; Reguant-Closa et al. 2024). Under this perspective, the accounting of land management, productive, and financial functions have been suggested in agricultural LCAs (Nemecek et al. 2015). In addition to this, an increase in interest in integrating nutritional function into food LCA has been recorded over the course of the last few years (McLaren et al. 2021; Ridoutt 2021; Nemecek et al. 2016). Besides, in selecting the best FU for the investigated system, it should also be considered that the function might considerably vary with the stakeholders' perspectives, mainly due to differences in their needs, interests, and final food product quality requirements and/or preferences (Berardy et al. 2020; Grassauer et al. 2022; Oldfield et al. 2018).

In this context, this article wishes to present an alternative perspective for best representing and modelling cereal-based cropping systems. In particular, the study adopts a new *combined* approach that allows for the impact assessment at the product level while accounting for inter-crop relations in a system perspective. Moreover, multiple FUs have been identified in a way that is explicitly aligned with the primary stakeholders' interests. The authors decided to analyze cereal crops, as they are known to be vital for producing staple foods but, at the same time, threaten ecosystem quality, especially when grown under intensive systems (Renzulli et al. 2015; Vinci et al. 2022). Attention was concentrated on two durum wheat (DW) (*Triticum turgidum* subsp. *durum* (Des.) Husnot) cropping systems, that were different in terms of crop rotation schedules, farming methods, tillage techniques, and genotypes grown. For article enrichment purposes, a photo of the organic DW landrace, taken by the authors during one of the visits in the cultivated field, is shown in Fig. 1.

The authors focused on DW, because it has been proven to be beneficial for human nutrition and health, but also responsible for severe environmental impacts (Shewry and Hey 2015; Zingale et al. 2022a). With regard to this last point, the major burdens have been reported to be mainly dependent upon:

- N_2O emissions, from both fertilization and crop-residue handling
- Diesel production and combustion for farming activities
- Fertilizer production and supply to the farming area (Tahmasebi et al. 2018).

Fig. 1 An organic durum wheat system in southern Italy, based on cultivating a landrace (*Ruscìa*). Photo credit: Farm managers of "Frantonio Società Agricola" in Ragusa (Sicily).

Accordingly, DW cultivation has been documented as a phase of DW's life cycle that highly contributes to climate change, biodiversity loss, and environmental degradation (Alhajj Ali et al. 2015; Gan et al. 2011; Heidari et al. 2017). Overall, it generates damages to human health, ecosystem quality, and resources, thereby emphasizing the need for improvements on the whole agricultural scale. On this subject, Zingale et al. (2022a) recently reported the results from a systematic literature review of LCAs in the DW sector and concluded that environmental improvements are urgently needed in DW cultivation systems, mainly through the implementation of agroecological practices. Based upon the findings of that SLR (Zingale et al. 2022a), two major research gaps in the DW LCA were identified and recommended to be filled, namely:

- The lack of integration of quality accounting into the LCA framework
- The limited attention paid to organic and low-input DW farming systems growing landraces and old varieties.

In contrast, landraces and old DW varieties have been rediscovered as a source of adaptive traits to local environmental conditions in the face of climate change, and germplasm with an enhanced nutritional and phytochemical profile (Zingale et al. 2023; Newton et al. 2010; Menga et al. 2023).

According to the authors, all of the above supports the rationale for this *multifunctional* LCA development, with the primary goals of:

- Evaluating the environmental impacts of ancient and modern DW cropping systems in a way that best represents their complexity and multifunctionality
- Identifying room for environmental improvements in the investigated systems
- Highlighting the influence that the methodological choices made have on the environmental assessment result.

In this way, the study aims at contributing to advancing LCA applications in the cereal farming field, and the scientific debate on the environmental advantages of alternative and low-input cropping systems.

2 Materials and method

An attributional LCA was developed with a "cradle-to-farm gate" approach, according to the specialized International Standards (ISO 2006), on two rainfed DW farming systems in Sicily, that had the following features:

- Case 1: a low-input, organic cropping system where DW grains are produced from the *Ruscìa* or *Russello Ibleo* Sicilian landrace
- Case 2: a conventional and high-input cropping system for production of DW grains from an improved variety called *Simeto*.

Specifically, landraces are defined as traditional and regional ecotypes with a high capacity to adapt to biotic and abiotic stress conditions, resulting in an intermediate and stable yield level under low-input agricultural systems (Villa et al. 2005). For completeness reasons, he following sections provide an in-depth description of the two case studies.

2.1 Case studies

Both investigated systems were located in Sicily, in the territories of Ragusa (Modica, RG, Sicily, 36°52′24.6″ N - 14°49′55.3″ E) (Case 1) and Ramacca (Ramacca, CT, Sicily, 37°23′46.7″ N - 14°39′23.1″ E) (Case 2). This region's climate is mainly Mediterranean, characterized by wet/mild winters and hot/dry summers. Recently, the annual rainfall has been slightly decreasing, whereas the mean temperature tended to increase, thus determining yield and quality uncertainty (Baiamonte et al. 2019; Guarnaccia et al. 2020). The Supplementary Materials (Tables S1 and S2, and Figure S1) reported the pedoclimatic conditions of the study's sites, the genotypes' agronomic and quality traits, and the time-based sequence of the agricultural activities carried out within the investigated systems. In Case 1, the Sicilian DW landrace, called *Russello Ibleo* or *Ruscìa* (Taranto et al. 2022), is organically grown in rotation with faba bean (FB) (e.g., *Vicia Faba* L.), while in Case 2, the modern variety is preceded by a year of bare fallow, during which only conventional tillage practices are carried out. The authors chose to investigate these two systems precisely, because of their substantial differences. In fact, such a diversity has been considered functional and ideal for satisfying one of the primary research objectives of the study, that is, to test an alternative combined modelling approach. Consequently, the two farms were actively involved in the research project to provide all technical data on agricultural activities carried out, input intensities, and yields. In addition, they provided grain samples for the qualitative analyses necessary for calculating the quality index used as one of the FU.

2.1.1 Case 1—DW landrace under an organic and low-input cropping system

Farmer 1 carried out the landrace's durum wheat cultivation under organic farming. Faba bean was grown before DW to make sure it could provide several environmental and economic benefits, including breaking disease cycles and providing the N supply to the following crop, thus reducing the need for N fertilizer application; and being sold to the local community, thereby generating additional revenue for the farmer. Furthermore, legumes could determine an improvement in the nutritional and technological quality of the DW that is cultivated next, mainly by increasing the quality and quantity of protein content (Gan et al. 2011; Grant et al. 2012; Ditzler et al. 2021). Especially faba bean is generally more effective in improving soil texture and fertility because its roots are rich in nodules that host efficient nitrogen-fixing Rhizobium bacteria (López-Bellido et al. 2003; Köpke and Nemecek 2010). Faba bean cultivation was characterized by organic fertilization with cattle manure (27.5 m^3/ha of manure, having a density of 0.8 t/m^3, and 3 kg N/t and 3.25 kg P2O5/t of manure) and reduced soil tillage operations. At the time of harvesting, faba bean straw was chopped and incorporated into the field. Tillage operations were carried out to prepare a suitable seedbed for germinating and establishing the durum wheat crop and included two harrowing operations. DW seeds were sown in November through a mechanical universal drill in rows spaced 20 cm and with a homogeneous depth of the seed of about 4 cm. Moreover, as landraces are known not to benefit from high rates of sowing and nitrogen-fertilization, due to their susceptibility to lodging, the farmer adjusted the amount sown grains to 180 kg ha^{-1}, and no fertilizers were applied throughout the entire crop cycle. Also, following the organic farming specifications, no herbicides or fungicides were applied. Accordingly, crop rotation with leguminous crops and the choice of a taller variety naturally promote a reduction in the weed intensity (van der Meulen and Chauhan 2017). Moreover, during the crop years considered, there has been no need to operate irrigation, as plants were naturally fed by autumn and winter rains. Finally, harvesting was done in July on mature DW spikes using a combine harvester, and no drying was carried out because, at the harvest, the grains had a low moisture content (lower than 14%).

2.1.2 Case 2—improved DW variety under high-input and conventional farming

The modern or improved variety (Simeto) was cultivated according to conventional practices, both in crop rotation, tillage techniques, fertilization, and plant protection treatments. Indeed, the farmer performed a durum wheat-bare fallow rotation (one crop in 2 years) to enhance water storage and ensure the emergence and establishment of the wheat seedling. This ancient agronomic practice involved using a moldboard plough as primary tillage and repeated secondary tillage to control weeds and water consumption (Devita et al. 2007). Nitrogen was split and applied at a 1/3 rate before sowing as diammonium phosphate, and 2/3 N top-dressed was applied at the beginning of durum wheat tillering as ammonium nitrate. Sowing was carried out at a high rate (220 kg grains ha^{-1}), always in November as for Case 1, by using a mechanical universal seed drill. Weeds were controlled utilizing specific herbicides containing the following active ingredients: Metsulfuron-methyl, iodosulfuron-metil-sodium, mefenpir-dietile, clopiralid, florasulam, and fluroxipir meptil. In addition, a fungicide based on Azoxystrobin was applied between early stem elongation and full flowering to prevent any spikes' diseases. As for Case 1, no irrigation was carried out, and the whole field was harvested mechanically in June. No drying was carried out because of the low grain moisture content.

2.2 Goal and scope definition

This multifunctional LCA was conducted with the following objectives:

- Comparing the environmental profiles of the two cropping systems, to identify the one that performed best
- Highlighting environmental hotspots and improvement potential for each cropping system investigated
- Ensuring that the methodological choices adopted in terms of system boundaries (SB), allocation criteria (AC), and FUs were able to capture the complexity and peculiarities of the two cropping systems.

The target audience for this study comprises producers, researchers, and policymakers interested in identifying strategies for more sustainable DW cropping systems.

2.2.1 System boundaries

Finding system boundaries that are equally valid both in agricultural practice and LCA models is an essential and relevant issue, as the quality of the representation they provide affects the quality and meaningfulness of the overall results (Brankatschk and Finkbeiner 2015). The authors conceived the faba bean cultivation and the bare fallow as the necessary and essential preparatory processes for DW-grain production in the following year. This was in line with:

- The farmers' awareness of the disadvantages of cereal continuous cropping (CC) systems in terms of control of weeds, soil quality, and requests for external inputs
- The Common Agricultural Policy (CAP) of the European Union (EU) and its funding mechanisms (e.g., agri-environment schemes or AES), which push producers to introduce legumes and fallow periods in their cereal-dominated crop rotations to achieve environmental and economic benefits (Dupraz and Guyomard 2019).

Indeed, for Case 1, the rotation with the faba bean was carried out to primarily provide the soil with the necessary N supply for the subsequent DW-landrace cultivation under low-input conditions and, secondarily, generate an additional proper income for the farmer. Instead, in Case 2, the bare fallow is carried out as an alternative to DW continuous cropping to avoid the disadvantages mentioned above, and a decline in DW yield in the long run. Thereby, from an LCA-application perspective, the legumes-derived N leftovers in the soil for Case 1 and the hectare associated with the agricultural activities of the one-year bare fallow for Case 2 were modelled as inputs in the main processes of DW cultivation. By doing so, the system boundaries were adapted at the level of the crop rotation, allowing for higher reliability in evaluating the environmental impacts (Figure 2).

From Figure 2, there is evidence that the main crop (durum wheat) is linked to its cropping system through the effects of the previous crop/non-crop. This differs from the conventional approach (*crop-by-crop*) used in *product* LCAs, where each crop is modelled and evaluated separately from its rotation (Charles et al. 2006; Tricase et al. 2018). It is also different from what is typically done in *system* LCAs, where the cropping system is conceived as a whole system, producing more co-products, each responsible for a share of the total environmental impacts (Nemecek et al. 2008, 2011a; Prechsl et al. 2017). The approach presented here can be defined, instead, as *combined*, considering that it makes it possible to assess the impacts of the individual crop production, while considering the main CR effects. Similar but more complicated approaches have already been presented in previous studies, such as Brankatschk and Finkbeiner (2015) and Peter et al. (2017). In contrast, the approach tested in this article is distinguished by its ease of use and specific applicability to cereal cropping systems, in

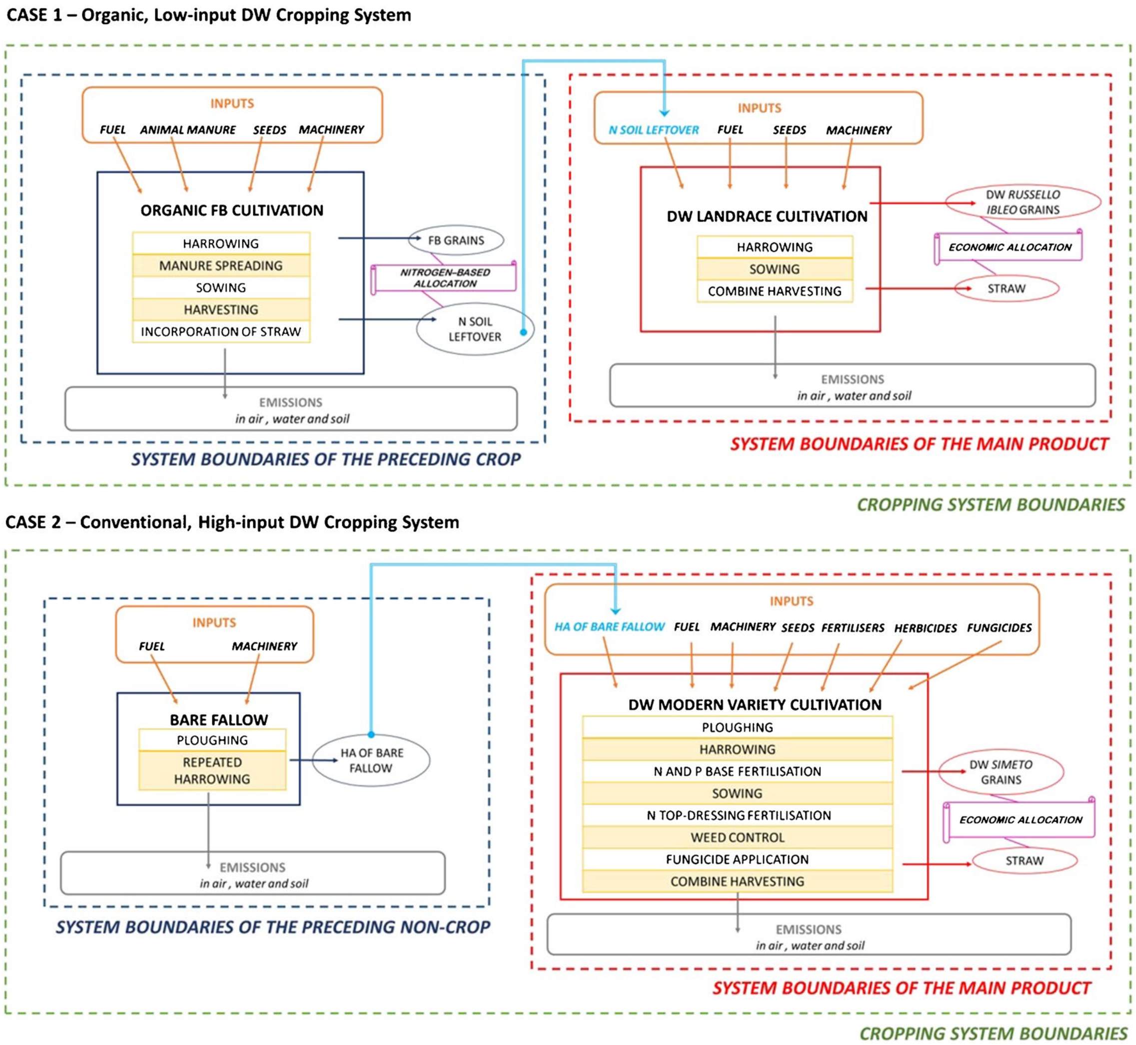


Fig. 2 System boundaries of the investigated durum wheat (DW) cropping systems according to the proposed *combined* and *multifunctional* approach. FB, faba bean; N, nitrogen; P, phosphorus; HA, hectare.

particular cereal-legume rotations, thus making it a valuable addition to the existing literature. According to the authors, this approach has the key features of respecting the rotational sequence from a temporal perspective, capturing the main function of each crop of the rotational system, considering the main inter-crop relations (CR effects), and enabling an equitable comparison between the two case studies. Indeed, by adopting this approach DW was automatically loaded with the benefits and impacts of being part of the rotation in both Cases 1 and 2.

2.2.2 Functional units

For this LCA development, the authors have particularly concentrated on aligning the system FUs with the perspectives of the main DW stakeholders that the authors identified as farmers and processors (i.e., millers and pasta factories). The consumer's perspective was not accounted for, as it was considered by the authors to fall outside of the aim and scope of the study, which was exclusively focused on DW grain production, e.g., the raw material for pasta processing. Specifically, concerning farmers' perspective, in line with Nemecek et al. (2011b), Cerutti et al. (2013), and Noya et al. (2018), the authors used:

- A product functional unit (kg of grain) reflecting the production of the grain
- A land-based functional unit (hectare per year), reflecting the agricultural use of the land to maintain its production
- A price-based functional unit (€), reflecting the generation of an adequate income from the sale of grain and straw.

Those three FUs were complemented with a quality-corrected FU, that represented the need for farmers to provide millers and pasta factories with a raw material feasible to be processed into semi-finished and finished products, thereby with grains having good technological features (Mefleh et al. 2019). Actually, this fourth FU allows for embracing two perspectives (that of farmers, and that of processors), as both the two stakeholders are interested in having an efficient exchange: in fact, a grain of poor quality is paid less to the farmer, and represents a problem for the processor in the production and marketing of DW-grain derivatives, like flour and pasta. Indeed, the quality of the final product is influenced by the quality of the grain and semolina which, in turn, are mainly controlled by genotypes, environmental conditions, and crop management systems. In line with this, the DW-related EU quality index (QI) reported in the European Commission Regulation No. 2237/2003 (EC 2003) was chosen for developing the quality-correlated FU. The QI consists of the sum of the averages of different quality parameters (such as protein content, gluten index, yellow index, and hectoliter weight) multiplied by their respective weighing values (40%, 30%, 20%, and 10%). To that end, 250 g sample grains produced by the two case farmers were randomly drawn from each field, cleaned, and used for quality determinations (the methods of analyses were reported in the Supplementary Material). An overview of the four FUs used were depicted in Fig. 3. There is evidence that all the three FUs (i.e., economic, land, and quality-correct) were directly or indirectly calculated from the mass-based one that, so, can be considered the reference FU of this study.

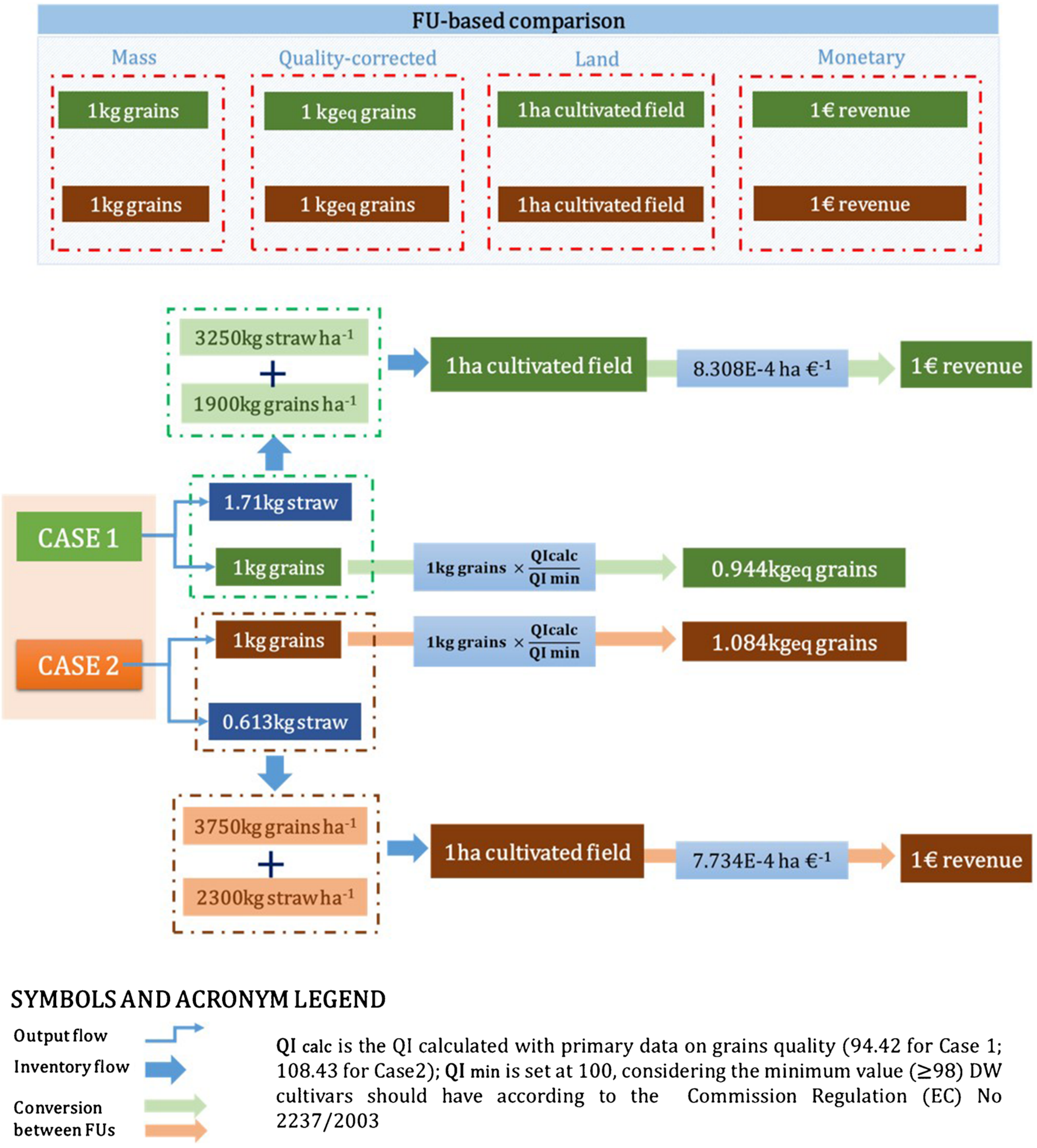
2.2.3 Allocation

This phase was carried out to best represent the functions of the different sub-systems, as comparisons between different farming systems may become biased in cases where the allocation rules miss reflecting system-specific differences (Meier et al. 2015).

For instance, with regard to the faba bean sub-system, an allocation based on the nitrogen (N) content was used to split the environmental burdens between faba bean grains and N soil leftovers. Faba bean straw was not regarded as a co-product, because it was entirely incorporated into the soil. Essential pieces of information on the N-fixation ability of faba bean were found in several manuscripts dealing with multi-year agronomic trials conducted under rainfed Mediterranean cropping systems, namely Sulas et al. (2013); Ruisi et al. (2017); López-Bellido et al. (2006); Palmero et al. (2022). For the modelling of faba cultivation in the Case-1 system, according to the hybrid approach described above, the authors used the values reported by Sulas et al. (2013) on faba bean's N concentration in grains (42 kg N/t), straw (12 kg N/t), roots (9 kg N/t), and N soil leftovers or N balance (31 kg N/ha). They did so because they considered those values to be well representative of the whole agricultural system investigated.

No allocation was performed for the bare fallow sub-system, as this activity did not provide marketable products and co-products but only implied monthly soil tillage operations to control weeds.

Concerning the DW cultivation sub-systems, both for Case 1 and Case 2, when the mass-based FU was considered, an economic criterion was adopted to allocate inventories and impacts between DW grains and straw. This allocation procedure was preferred, as both co-products (i.e., grains and straw) are sold, and their market prices differ widely one another (Ardente and Cellura 2012). The prices were gathered by the interviews with the farmers supporting the study, and cross-checked with the wholesale price lists published by the Foggia Stock Exchange (CCIA-FG 2023) to take advantage of more reliable data. The yield and price mean values, and variations over the years of collection of the data were reported in Table S4 of the Supplementary



QI calc is the QI calculated with primary data on grains quality (94.42 for Case 1; 108.43 for Case2); QI min is set at 100, considering the minimum value (≥98) DW cultivars should have according to the Commission Regulation (EC) No 2237/2003

Fig. 3 Modelling of the functional units (FUs) adopted within the study. DW, durum wheat; QI, quality index; QIcalc, quality index calculated; QImin, quality index at the minimum value

Materials. From the latter, it was clear that both grains and straw yields, and selling prices were highly different between the two investigated systems as a consequence of the diverse grown genotypes and farming regimes. Especially, the landrace produced a larger amount of straw (Table S4) due to its high plant height, resulting in a low harvest index. Thus, in Case 1, a mass-based allocation would have mistakenly brought out straw as the main product, thereby questioning the key function of the cultivation system, that is, to produce grains (Zingale et al. 2022b). Thereby, the economic allocation was necessary and useful for modelling the grains as the core product of the investigated systems, as also stated by Zingale et al. (2022b). Also, the selling prices of both grains and straw were higher in Case 1 because of the product type, which was organic and traditional (Table S4). Indeed, the production of certified organic wheat allowed it to maintain a premium price compared with the conventional market (Migliorini et al. 2016).

The following formulas were used for the calculation of the allocation percentages:

- *Allocation based on N-content (for faba crop)*

$$AP_{Ngrain} = \frac{Q_{Ngrain}}{\left(Q_{Nsoilleftovers} + Q_{Ngrain}\right)} \times 100$$

$$AP_{Nleftover} = \frac{Q_{Nsoilleftovers}}{\left(Q_{Nsoilleftovers} + Q_{Ngrain}\right)} \times 100$$

- *Economic allocation (for DW crop)*

$$AP_P = \frac{Q_P \times MP_P}{\left[(Q_P \times MP_P) + (Q_{CP} \times MP_{CP}\right]} \times 100$$

$$AP_{CP} = \frac{Q_{CP} \times MP_{CP}}{\left[(Q_P \times MP_P) + (Q_{CP} \times MP_{CP}\right]} \times 100$$

in which:

- AP is the allocation percentage calculated [%]
- Q is the quantity of product (P), co-product (CP), or nitrogen (N) [kg]
- N_{grain} is the kg of N exported by grain per hectare, while $N_{soil\ leftovers}$ is the kg of N per ha left in the field after harvest; N_{grain} was calculated by multiplying the nitrogen content per tons of faba bean grains on a dry matter basis (kgN tons DM^{-1}) by the faba bean grain yield per hectare (tons ha^{-1})
- MP is the market price for both the P and CP [€].

Hence, by applying these formulas, the following allocation percentages were obtained:

- 73.53% for faba bean grains, and 26.47% for N soil leftovers
- 80.42% for *Ruscìa* durum wheat grains, and 19.58% for its straw, within Case 1
- 92% for *Simeto* durum wheat grains, and 8% for its straw, within Case 2

Information about the allocation procedures and production yields were summarized in Table S3 of Supplementary Materials.

2.3 Life cycle inventory analysis

Primary data on agricultural inputs, farming practices, resource consumption, yields, and market prices were obtained through interviews and questionnaires with the farmers. Such data have been collected, analyzed, and elaborated between July 2022 and July 2023, and are referred to the four growing seasons from 2018/2019 to 2021/2022. Those in the middle, namely 2019/2020 and 2020/2021, were modeled, despite the rampant Covid-19 pandemic because farming activities were carried out the same. As regards background data, the agrochemical production, the fuel-combustion-derived emissions during field operations, and material-input acquisition transports were assessed through the Ecoinvent v. 3.6 database, as available in Simapro 9.1.0.11 (Moreno Ruiz et al. 2017; Wernet et al. 2016). The latter was used, because it is recognized as comprising most of the background materials and processes required in agricultural and food LCAs (Frischknecht and Rebitzer 2005). However, the Ecoinvent farming-treatment modules needed adjustments: these were made by the authors by replacing the background diesel consumption values with the primary system-specific ones provided by the farmers. Subsequently, the authors modulated the emissions of GHGs and other pollutants coming from those diesel requirements combustion, using a correction factor that was represented by the ratio between the system-specific (primary) data and the Ecoinvent (secondary) data of diesel consumption (Ingrao et al. 2018). In addition to this, they calculated the process-specific mass-quantity of the tractor and the agricultural machinery utilized for the given farming treatment (FT) per ha of cultivated field, so expressed as kg/ha. They did that, by multiplying the related mass/service-life ratio (kg/h) as available in Ecoinvent, by the specific FT time (h/ha). The authors concluded such a data elaboration procedure, by adjusting the tire-abrasion derived emissions to the soil that, as the diesel-combustion-derived ones, are already contained in the Ecoinvent module of the given FT. To that end, they calculated the ratio between the primary and the secondary data of tractor's mass quantity and used it as a correction factor.

Direct field emissions were calculated using the models described in the Methodological Guidelines for the Life Cycle Inventory of Agricultural Products, published in 2019 as a result of the World Food LCA Database (WFLDB) project (Nemecek et al. 2019). Especially, ammonia (NH_3), nitrous oxide (N_2O), nitrate (NO_3^-), heavy metals, and phosphate (PO_4^{3-}) emissions were computed using the methods provided by EEA (2019), IPCC (2019b), SQCB-NO3 model (Faist Emmenegger et al. 2009), SALCA-heavy metal (Freiermuth 2006) and SALCA-P (Prasuhn 2006), respectively.

As far as the NO3 emissions were regarded, in the case of bare fallow, the SQCB-NO3 model was used by computing a root depth of 1 m, assuming DW roots remain in the soil after harvesting, and other weed plants grow during the bare fallow year.

The manure-derived emissions in the fava bean cultivation were measured only for the spreading process, not for the production and storage, which were considered outside the system boundaries. No phosphorus emissions through water erosion were estimated, since the two site fields were not particularly sloping.

Pesticide emissions, due to the application of the post-emergence herbicides and the fungicide, were calculated and distributed to the different environmental compartments (air, agricultural soil, forestry soil, and water) using the default fractions provided by the OLCA-Pest Project, considering the scenarios for *Pooideae* crops, without buffer zone (Nemecek et al. 2022).

Data inventories of faba bean and bare fallow sub-systems can be found in the supplementary materials (Table S5 and S6), while those related to DW cultivation were reported in Table 1. The latter shows the inventories for production of the total raw biomass produced (i.e., grains + straw) in the high-input and low-input systems, respectively. The contribution from each of the two biomass elements to those inventories and resulting environmental impacts can be extrapolated by applying the above calculated economic allocation percentages. Thereby, Table 1 displays differences in output, input, agricultural activities, and emissions are quantitatively expressed.

2.4 Life cycle impact assessment

This phase was conducted by using the ReCiPe 2016 v. 1.04 methodology, as available in Simapro 9.1.0.11, at the midpoint and endpoint levels, assuming a hierarchical (H) perspective. The latter was chosen, because it is known to guarantee scientific validity with regard to both the time frame and plausibility of impact mechanisms, as highlighted by Huijbregts et al. (2017). One more reason why the authors selected this method for their LCIA development is that it is extensively documented in the specialized literature to be particularly suited for comparing organic and conventional cultivation systems (Coppola et al. 2022). In fact, it includes different toxicity-related impact categories, really helpful in accounting for the differences in the use of pesticides between organic and conventional agronomic managements (Coppola et al. 2022).

The choice of using both the midpoint and endpoint approaches was derived from the intention of the authors to provide highly understandable results for the target audience of the study and, at the same time, perform a very comprehensive analysis of the impacts that could be easy to understand and reproduce. The endpoint results are, in fact, concise and easier to interpret, while the midpoint ones are complete and more certain. However, midpoint results are, not fully suitable for holistic judgments of products' profiles, given that they are expressed with different equivalent units of measure (Ingrao et al. 2024). Especially as this study was targeted to a wide audience that includes farmers, producers, managers, and scholars, the endpoint analysis was considered essential to smartly and efficiently communicate the ultimate and most relevant damages at the three areas of protection, namely human health, ecosystem, and resources (Ingrao and Wojnarowska 2023; Ingrao et al. 2024). Differently, the adoption of the only midpoint approach would have made the overall interpretation of the results difficult, as it concludes a set of indicators for too many different impact categories, without a univocal aggregated evaluation of the product's environmental profile (Ingrao et al. 2024). At the same time, the midpoint approach was considered equally important, as it explicitly addresses environmental impacts related to agricultural production, delivers results more closely linked to the inventory data, is easier to verify and compare across studies, and allows for a more detailed and specific analysis of the impacts (Dong and Ng 2014).

3 Results and discussion

Results from this study were presented following a top-down approach, that started from giving the general, and mostly relevant picture of the environmental burdens of the two investigated systems; thereafter, they proceeded with a more detailed and specific level of analysis. At the end final remarks were drawn. Accordingly, this section was structured into the following sub-sections: Sect. 3.1, Endpoint analysis; Sect. 3. 2, Midpoint analysis; and Sect. 3.3, Final considerations. Endpoint results were displayed at the weighing and damage assessment stages; while the midpoint ones were expressed as they come from the characterization step of the analysis.

3.1 Endpoint analysis

The results obtained at the endpoint level demonstrated that the conventional high-input durum wheat system was always more impacting than the organic low-input one, regardless of the functional unit adopted. Indeed, as illustrated in Figure 4 and reported also in Table 2, for all FUs adopted, the total damage scores were considerably higher for the conventional high-input system. In particular, Figure 4 shows the total scores (expressed in millipoints or points as a result of the weighting process), while Table 2 specifies the scores and the damage assessment results per Area of Protection (AoP) or damage category.

Based on Figure 4 and Table 2, "Ecosystems" was found to be the most affected AoP for both investigated systems, followed by "Human health" and "Resources". The latter contributed minimally to the total score (on average, 0.53 % between the two systems) compared to the other two AoP, and in both cases, it was mainly due to diesel consumption for soil tillage operations and agricultural practices, such as sowing, combine harvesting and baling. Furthermore, it was noticed (Figure 4) that the differences in total damages between the two systems were more pronounced when the hectare and revenue functional units were adopted. The authors attributed this to the results being less influenced by yield differences and allocation percentages when these

Table 1 The durum wheat (DW) cultivation data inventory refers to the total raw biomass produced, comprising grains and straw: specifically, 2.71 kg/kg grain for the organic low-input system (equivalent to 5.262E-04 ha) and 1.613 kg/kg grain for the conventional high-input one (equivalent to 2.67E-04 ha). *UM* unit of measurement.

Low-input organic DW system (Case 1)		High-input conventional DW system (Case 2)		
Outputs		*Outputs*		UM
DW *Ruscìa* Ibleo grain	1	DW *Simeto* grain	1	kg
DW *Ruscìa* Ibleo straw	1.71	DW *Simeto* straw	0.613	kg
INPUTS		*INPUTS*		
Resources		*Resources*		
Occupation, annual crop, non-irrigated, extensive	5.262E−04	Occupation, annual crop, non-irrigated, intensive	2.67E−04	ha yr
Crop rotation effects		*Crop rotation effects*		
N soil leftovers from faba bean cultivation (kg)	1.63E−02	Bare Fallow (ha)	2.67E−04	
Materials		*Materials*		
Self-produced *Ruscìa* seeds for sowing	9.47E−02	Conventional seeds for sowing	5.87E−02	kg
		Ammonium nitrate, as N	6.94E−03	kg
		Diammonium phosphate, as N	1.44E−02	kg
		Diammonium phosphate, as P2O5	2.46E−02	kg
		Pesticide, unspecified	9.66E−04	kg
		Tap water	4.75E−01	kg
		Fatty alcohol sulfate	2.75E−04	kg
Agricultural activities		*Agricultural activities*		
Tillage, harrowing, by offset disk harrow	5.262E−04	Tillage, harrowing, by offset disk harrow	2.67E−04	
Sowing	5.262E−04	Sowing	2.67E−04	ha
Combine harvesting	5.262E−04	Combine harvesting	2.67E−04	ha
Baling processing	4.736E−03	Baling processing	1.60 E−03	p
		Tillage, ploughing	2.67E−04	ha
		Rock picking	2.67E−04	ha
		Base Fertilizing	2.67E−04	ha
		Dressing Fertilizing	2.67E−04	ha
		Field spraying of herbicides	2.67E−04	ha
		Field spraying of fungicides	2.67E−04	ha
Transports	7.58E−01	*Transports*	3.84	kg km
Direct emissions		*Direct emissions*		
To air		*To air*		
Dinitrogen monoxide	3.046E−4	Dinitrogen monoxide	4.79E−04	kg
		Ammonia, IT	1.86E−03	kg
		Nitrogen oxides, IT	2.12E−04	kg
		Azoxystrobin	6.68E−03	g
		Starane	3.70E−04	g
		Clopyralid	2.05E−04	g
		Metsulfuron-methyl	4.87E−04	g
		Emission, unspecified	1.20E−03	g
To water		*To water*		
Nitrate	7.35E−02	Nitrate	2.88E−02	kg
Phosphate (leaching)	8.12E−04	Phosphate acid (leaching)	1.87E−05	kg
Phosphate (run-off)	9.21E−05	Phosphate acid (run-off)	6.28E−05	kg
Cadmium	4.64E−04	Cadmium	1.26E−02	mg
Chromium	2.10E−02	Chromium	5.48	mg
Copper	5.37E−02	Copper	4.84E−01	mg
Lead	6.27E−05	Lead	7.57E−02	mg
Mercury	2.09E−06	Mercury	2.30E−04	mg
Zinc	1.01	Zinc	6.49	mg

Table 1 (continued)

Low-input organic DW system (Case 1)		High-input conventional DW system (Case 2)		
Outputs		*Outputs*		UM
		Azoxystrobin	1.41E−05	g
		Starane	7.79E−07	g
		Clopyralid	4.32E−07	g
		Metsulfuron-methyl	1.03E−06	g
		Pesticides, unspecified	2.53E−06	g
To agricultural soil		*To agricultural soil*		
Cadmium	−1.61	Cadmium	−9.02E−01	mg
Chromium	−3.10E−01	Chromium	−5.49	mg
Copper	1.02E+01	Copper	4.64	mg
Lead	2.82	Lead	1.30	mg
Mercury	−2.18	Mercury	−1.20	mg
Nickel	1.23	Nickel	5.44E−01	mg
Zinc	2.47E+01	Zinc	6.69	mg
		Azoxystrobin	5.97E−02	g
		Starane	3.30E−03	g
		Clopyralid	1.83E−03	g
		Metsulfuron-methyl	4.35E−03	g
		Pesticides, unspecified	1.07E−02	g
To forestry soil		*To forestry soil*		
		Azoxystrobin	4.08E−04	g
		Starane	2.26E−05	g
		Clopyralid	1.25E−05	g
		Metsulfuron-methyl	2.97E−05	g
		Pesticides, unspecified	7.34E−05	g

FUs were used. Regarding the quality-corrected functional unit, its use made it possible to properly adjust the impacts depending on the grains' quality features (Figure 4 and Table 2). As expected, compared to the impacts per kg of grain, those expressed by the quality-corrected functional unit were increased for Case 1 (+5.61%; from 42.05 to 44.55 mPt) and decreased for Case 2 (−7.53%; from 49.56 mPt to 45.83 mPt), based on the level of technological quality assessed. Indeed, despite the appreciable commercial and technological features (especially the increased protein content), the *Ruscìa* grains achieved a QIcalc lower than the QImin, mainly due to its low gluten index (equal to 45.9%). On the contrary, the improved variety performed a higher QIcalc, mainly because of its very strong gluten (Gluten index = 89%). Such a result was consistent with several studies, including Nazco et al. (2012) and Rosello et al. (2018), which found a strong positive correlation between the QI and gluten strength, and modern varieties having higher QI values but lower grain protein content, compared to landraces. Therefore, adopting the quality-corrected functional unit turned out to be valid for considering both production's magnitude and quality constraints. In fact, using it determined an important reduction in the gap between the two systems, though the conventional and high-input one still remains the one causing the greatest environmental damage. On the other hand, the organic and low-input one was confirmed to have a slightly lower environmental impact, under this FU. After outlining the environmental performances of the two systems investigated, the authors performed a contribution analysis with the mass-based FU to precisely identify:

- Which processes (including inputs, emissions, and practices) caused the largest impacts and damage
- Which impact categories were the most relevant for the system investigated.

Figure 5 displays IC-related results expressed in mPt per kg of grain.

As shown in Fig. 5, the impacts were distributed similarly along the processes, even if they were of different magnitude between the two investigated systems. The primary hotspot for the conventional and high-input system was the bare fallow, resulting in a highly impacting and inefficient rotational choice (Figure 5). Instead, the main hotspot for the organic and low-input system was the increased land occupation due to the lower grain yield (Figure 5). The latter result

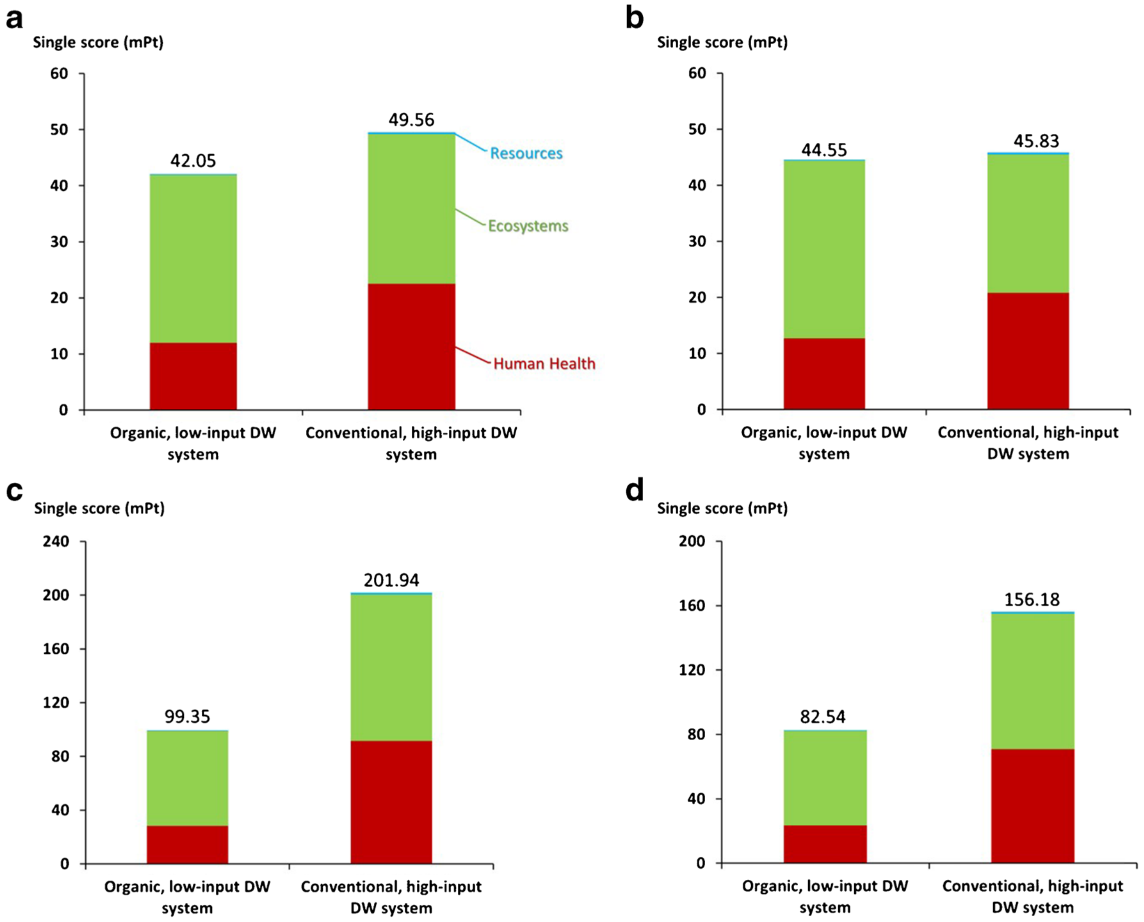


Fig. 4 Results of the end-point LCA assessment, expressed with different functional units: **a** mass-based, **b** quality-corrected, **c** land-based, and **d** price-based. DW, durum wheat; mPt, millipoints; Pt, points.

Table 2 Damage assessment (columns 3–5) and weighing results (columns 6–8) of the investigated DW cropping systems. Both refer to the different functional units (FUs) adopted in this study. *AoP* area of protection, *HH* human health, *E* ecosystems, *R* resources, *UM* unit of measurement, *DALY* disability-adjusted life year; *species·yr* loss of local species per year, *USD2013* additional dollar cost of future resource extraction, *Pt* point.

FU	AoP	Case 1	Case 2	UM	Case 1	Case 2	UM
Mass	HH	7.13E−07	1.33E−06	DALY	1.20E−02	2.25E−02	Pt
	E	5.35E−08	4.79E−08	species·yr	2.99E−02	2.67E−02	Pt
	R	2.03E−02	4.99E−02	USD2013	1.45E−04	3.56E−04	Pt
Quality	HH	7.55E−07	1.23E−06	DALY	1.27E−02	2.08E−02	Pt
	E	5.67E−08	4.43E−08	species·yr	3.17E−02	2.47E−02	Pt
	R	2.15E−02	4.62E−02	USD2013	1.54E−04	3.30E−04	Pt
Land	HH	1.68E−03	5.44E−03	DALY	2.84E−02	9.15E−02	Pt
	E	1.27E−04	1.95E−04	species·yr	7.07E−02	1.09E−01	Pt
	R	4.80E+01	2.03E+02	USD2013	3.43E−04	1.45E−03	Pt
Price	HH	1.40E−06	4.20E−06	DALY	2.36E−02	7.08E−02	Pt
	E	1.05E−07	1.51E−07	species·yr	5.87E−02	8.43E−02	Pt
	R	3.99E−02	1.57E−01	USD2013	2.85E−04	1.12E−03	Pt

confirmed the findings of several LCAs comparing organic and conventional systems, including Tuomisto et al. (2012) and Verdi et al. (2022), who underlined that organic farming usually requires more land to achieve good productivity levels (Boschiero et al. 2023)

From Figure 5, it was also evident that *Land Use* was the most affected impact category for both the investigated systems, followed by *Fine Particulate Matter Formation*, *Climate Change (Human Health)*, and *Human Non-Carcinogenic Toxicity*. Indeed, these four ICs contributed for

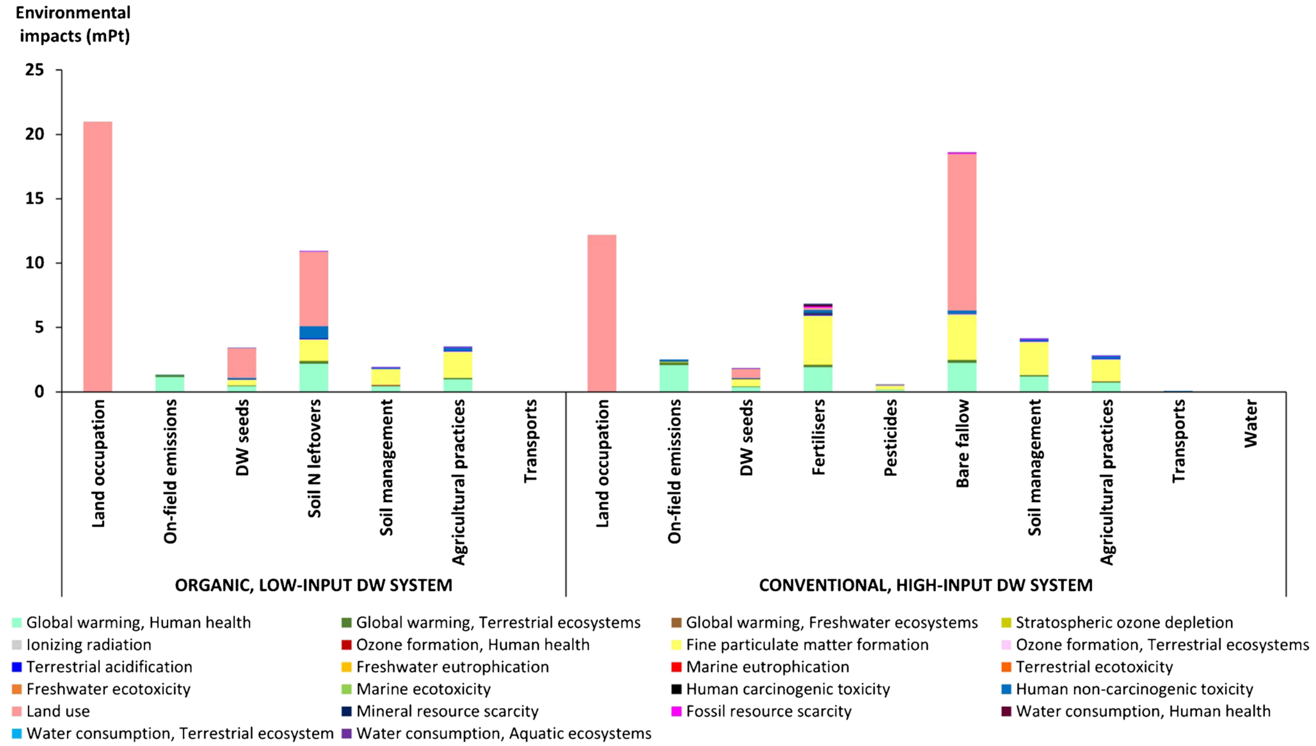


Fig. 5 Results of the end-point assessment per impact category, with kg of grain as a functional unit. DW, durum wheat; N, nitrogen; mPt, millipoints. "On-field emissions" is referred to the all substances emitted in air, water, and soil, at the field level, thereby those calculated by the authors during the inventory phase, using the models listed in Sect. 2.3

more than 95% to the total damage score, as clearly shown in Figure 6 and Table 3.

The integrated discussion on the four most environmentally significant ICs, based upon the contributing processes (Figure 5) and the assessed results (Figure 6 and Table 3), was completed with a focus on the most contributing substances identified per kg of grain using a 1% cut-off. These results are shown in Table 4.

Concerning *Land Use,* the impacts between the two systems were close and precisely slightly higher for the organic and low-input one (29.10 mPt vs 25.32 mPt, as reported in Table 3). In fact, although the contribution of the soil N leftovers from faba bean was less impactful than the respective bare fallow in the conventional system, the land occupation impacts due to the cultivation and seed production of the durum wheat landrace were higher because of the limited grain yield per hectare achieved. Such a result reads as the importance of considering crop-rotation effects in the LCA analysis and points out the primary urges of increasing productivity under low-input conditions in Case 1 and changing

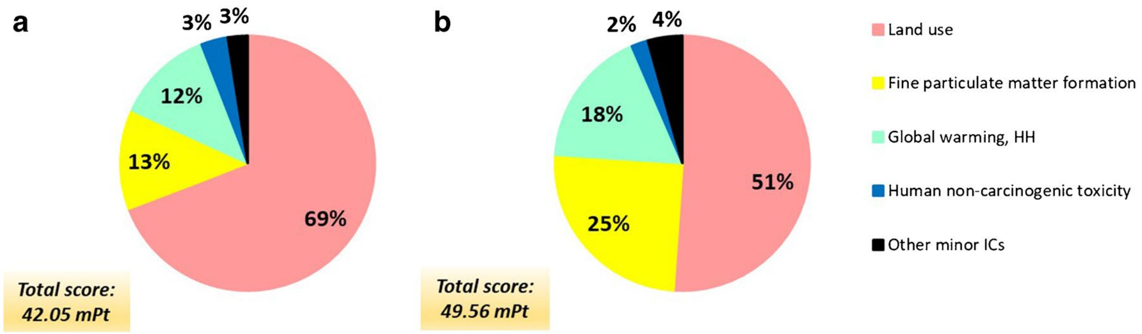


Fig. 6 Contribution percentages to the total damage per impact categories (ICs), as referred to the mass-based functional unit. **a** Case 1; **b** Case 2. HH, human health; mPt, millipoints.

Table 3 Damage assessment (columns 2–4) and weighing results (columns 5–7) for the most affected impact categories, referred to the mass-based functional unit. *HH* human health, *UM* unit of measure, *DALY* disability-adjusted life year, *species·yr* loss of local species per year, *mPt* millipoints.

Impact category	Case 1	Case 2	UM	Case 1	Case 2	UM
Land use	5.21E−08	4.53E−08	species·yr	29.10	25.32	mPt
Fine particulate matter formation	3.15E−07	7.33E−07	DALY	5.30	12.34	mPt
Global warming, HH	3.07E−07	5.14E−07	DALY	5.16	8.65	mPt
Human non-carcinogenic toxicity	8.47E−08	6.29E−08	DALY	1.43	1.06	mPt

Table 4 Substances emitted and resources consumed (output inventories), identified with a cut-off of 1% per impact category, referred to the mass-based functional unit; the two columns under the headings *amount* and *endpoint values (Pt)* are referred to Case 1 (on the left) and Case 2 (on the right). *HH* human health, *Pt* points.

Impact category	Substance and compartment	Amount		Endpoint values (Pt)	
Land use	Occupation, annual crop, non-irrigated, extensive (raw)	5.87m2·yr	x	29.1	x
	Occupation, annual crop, non-irrigated, intensive (raw)	x	2.60 m2·yr	x	12.9
	Occupation, cropland fallow (raw)	x	2.46 m2·yr	x	12.2
Fine particulate matter formation	Particulates <2.5 μm (air)	221 mg	524 mg	2.34	5.55
	Nitrogen oxides (air)	51 mg	207 mg	2.16	2.82
	Sulfur dioxide (air)	0.187 g	1.24 g	0.572	3.79
	Ammonia (air)	90 mg	66 mg	0.229	0.17
Global warming, HH	Dinitrogen monoxide (air)	629 mg	719 mg	2.93	3.36
	Carbon dioxide, fossil (air)	139 g	326 g	2.18	5.09
	Methane, fossil (air)	x	316 mg	x	0.178
Human non-carcinogenic toxicity	Zinc (soil)	29 mg	10 mg	1.11	0.530
	Zinc (water)	5 mg	9 mg	0.154	0.256
	Cadmium (soil)	−1.09 mg	-0.82 mg	0.126	0.0197
	Arsenic (water)	x	287 μg	x	0.0934
	Arsenic (air)	x	81 μg	x	0.0429
	Zinc (air)	x	1 mg	x	0.0355
	Lead (air)	x	282 μg	x	0.0305
	Mercury (water)	x	123 μg	x	0.0265

crop rotation schedules, avoiding unnecessary agricultural operations, and internalizing the environmental costs of agricultural inputs in Case 2. Regarding *the Fine Particulate Matter Formation*, the authors found that it was caused mainly by the emissions of particulates with a diameter <2.5 μm, sulfur dioxide, and nitrogen oxides during the soil tillage operations, fertilizer production, and combined harvesting operations (Table 4). As a consequence, this impact was more severe in Case 2 (Figure 6 and Table 3), which means for the system that relied more on tillage operations and fertilizer application. In fact, primary and secondary soil tillage operations from bare fallow and durum wheat cultivation, and fertilizer production and application accounted for 48.6 % and 30.6% of the total particulate matter formation potential, respectively. *Global warming (HH)* was associated with on-field emissions, crop rotation effects, fertilizer production, soil management, agricultural practices, and seed production (Figure 5). Even for this impact category, the conventional high-input system performed worse because of the intensive farming regime adopted, characterized by increased mechanization of production and high fertilizer use. In particular, it was noticed that the main GHG emitted for this system (Case 2) was CO_2, while for Case 1 it was the N_2O. According to the authors, this should be attributed to the very different agronomic management between the two investigated systems.

Human Non-Carcinogenic Toxicity accounts for the environmental persistence, accumulation in the human food chain, and toxicity effects of non-carcinogenic chemicals, such as heavy metals. By specifying the impacts per substance, the authors found that zinc was the substance that mostly contributed to the toxicity impact for both the investigated systems (Table 4). Such impact was slightly higher in the organic and low-input system (1.43 mPt, as reported in Table 3) because of the crop rotation effect of faba bean. As a matter of fact, both zinc contents of faba bean seeds and cattle manure, as extrapolated from the SALCA heavy metal model, were very high, as well as the respective leaching rates. However, this result was valid only when the mass-based and quality-corrected FUs were adopted, while by the land and price-based FUs, the human non-carcinogenic toxicity impacts of the organic low-input system were lower. The reader is referred to Table S7 in the Supplementary Materials for end-point result comparisons on different FU bases.

3.2 Midpoint analysis

Environmental impacts at the midpoint level were also reported in order to provide a more accurate understanding of the environmental criticalities characterizing the two investigated cropping systems. In particular, Table 5 shows the characterization values assessed for the four most relevant ICs (based on Figure 6) using the study's multiple FUs. It should be noted that the value of global warming potential (GWP) reported in Table 5 is total, as the distinction between, global warming human health, terrestrial ecosystems, and freshwater ecosystems, according to the ReCiPe method, is made only at the end-point level (Figures 5 and 6).

As expected, the midpoint results were in line with those above discussed at the endpoint level, thus confirming lower impacts for Case 1 as compared to Case 2, except for the Land Occupation Potential (LOP) and the Human Toxicity Potential non-cancer (HTPnc) when the mass-based and quality-corrected FUs were used (Table 5). For completeness, Table S8 of the Supplementary Materials reports the most emitted substances associated with the main ICs, along with their characterization values, expressed on the mass-based FU basis. In particular, meaningful differences were found in terms of GHG emissions between the two systems. These differences, which were already noticed at the end-point level (Table 4), were better explained at the midpoint one by presenting a contribution analysis (Figure 7) for the greenhouse gases (GHGs), all of them expressed in kgCO2 equivalents per kg of grain.

As shown in Figure 7, the main GHG emitted for Case 2 was CO_2 from bare fallow, tillage operations, and inputs production, followed by N_2O on-field emissions and CH_4 from fertilizer production. N_2O comes also from the bare fallow (Figure 7), as indirect emission from nitrate leaching. Instead, for Case 1, the substance that mainly contributed

Table 5 Midpoint LCA *result* regarding the most affected impact categories of the investigated systems. *LOP* agricultural land occupation potential, *PMFP* particulate matter formation potential, *GWP* global warming potential, *HTPnc* human toxicity potential (non-cancer).

	Case 1				Case 2			
Impact category	Mass	Quality	Land	Price	Mass	Quality	Land	Price
LOP (m2·yr crop eq)	5.87E+00	6.22E+00	1.39E+04	1.15E+01	5.11E+00	4.73E+00	2.08E+04	1.61E+01
PMFP (kg PM2.5 eq)	5.01E−04	5.30E−04	1.18E+00	9.83E−04	1.17E−03	1.09E−03	4.75E+00	3.68E−03
GWP (kgCO2eq)	3.30E−01	3.50E−01	7.80E+02	6.48E−01	5.53E−01	5.12E−01	2.26E+03	1.74E+00
HTPnc (kg 1,4-DCB)	3.71E−01	3.93E−01	8.77E+02	7.29E−01	2.76E−01	2.55E−01	1.12E+03	8.70E−01

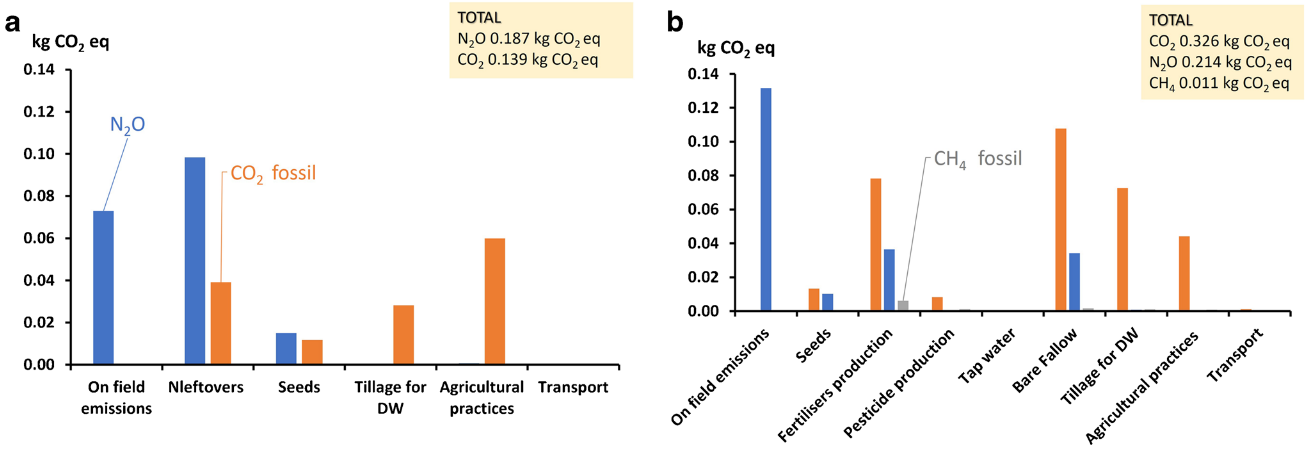


Fig. 7 Contribution analysis for the greenhouse gasses emitted with kg of durum wheat (DW) grain as the functional unit. **a** Case 1; **b** Case 2; N, nitrogen.

to the potential impact of global warming was N_2O, which came primarily from the FB crop rotation effect and then from on-field emissions. Indeed, the N_2O emissions associated with the FB sub-system were particularly high (Table S5) by reason of the combined effect of manure application, crop residue decomposition, and nitrate leaching. Similarly, during the following year (e.g., the DW landrace cultivation), despite no fertilizers were applied, the assessed N_2O emissions were quite high as a consequence of the leaching process. The latter, in fact, severely occurred, mainly as the consequence of soil and climatic conditions of the cultivation areas (especially, reduced soil clay content, high humus, and increased rainfall). The concurrence of these factors well explains why N_2O was so increased in Case 1, contributing to 56.77% of the total GHG emissions. However, even for the conventional and high-input system (Case 2), the N_2O contribution to the total GHG emissions was relevant, being equal to 38.74%. These findings were in line with those from the studies of Biswas et al. (2008) and Alhajj Ali et al. (2017), who stressed the importance of reducing N_20 emissions in wheat cultivation. In fact, considering that N_2O has a much higher global warming potential than CO_2 and a longer lifespan, it becomes crucial to reduce this kind of emissions, by practicing improved management strategies that release N more efficiently to crops.

In addition, the midpoint analysis also provided meaningful insights on the ICs that were considered minor based on the end-point weighing process, thus ensuring a broader and more comprehensive overview of the impacts. Figure 8 allows for a comparison of the two investigated systems on the basis of the midpoint results, as expressed through the totality of the ReCiPe method's ICs and by all the study's FUs. In particular, also at this analysis level, the authors noticed more marked differences when the land and price-based functional units were adopted.

Especially from Figure 8, it was possible to argue that, the organic low-input system always performed better than the conventional high-input one, except for land occupation (LOP), marine eutrophication (MEP), and human non-carcinogenic toxicity (HTPnc), when the mass-based and

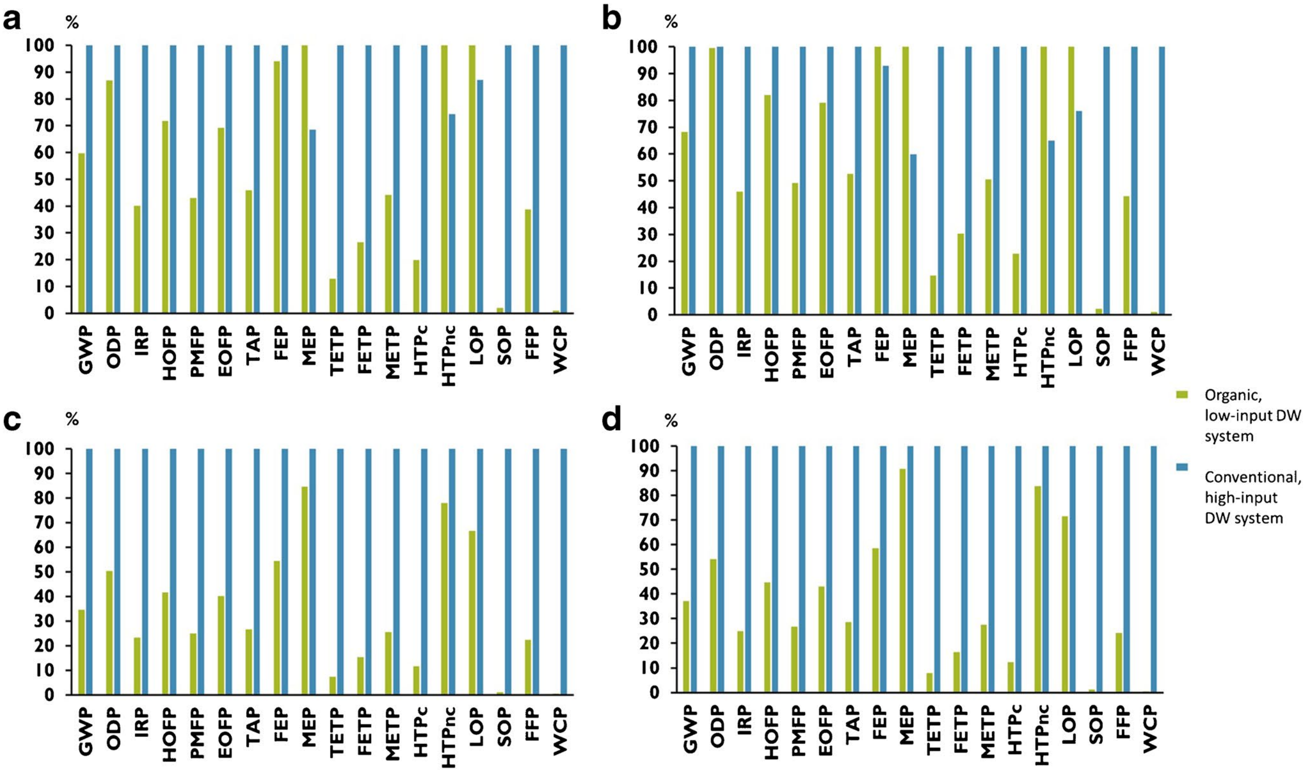


Fig. 8 Midpoint results are expressed as relative differences (%) between the investigated systems, using different functional units: **a** mass-based, **b** quality-corrected, **c** land-based, and **d** price-based. DW, durum wheat; GWP, global warming potential; ODP, ozone depletion potential; IRP, ionizing radiation potential; HOFP, photochemical oxidant formation potential (humans); PMFP, particulate matter formation potential; EOFP, photochemical oxidant formation potential (ecosystems); TAP, terrestrial acidification potential; FEP, freshwater eutrophication potential; MEP, marine eutrophication potential; TETP, terrestrial ecotoxicity potential; FETP, freshwater ecotoxicity potential; METP, marine ecotoxicity potential; HTPc, human toxicity potential (cancer); HTPnc, human toxicity potential (non-cancer); LOP, agricultural land occupation potential; SOP, surplus ore potential; FFP, fossil fuel potential; WCP, water consumption potential.

quality-corrected functional units were used. The reasons for the higher LOP and HTPnc impacts of Case 1 were already discussed above in the article. With regard to MEP impacts, those were dominated by the nitrate leaching process, which was considerably stronger in Case 1 than in Case 2. Such a difference was primarily attributed to the specific pedoclimatic conditions of Case 1, particularly the lower soil clay content, higher soil humus content, and higher precipitation rate (Table S1), all of these being environmental factors that are able to increase the leaching process. To verify this hypothesis, the authors performed a sensitivity analysis by assuming Case 2 soil and climate conditions for Case 1 and keeping all other production parameters constant.

From this analysis, NO3 leaching from cultivation of DW landrace and the preceding FB was reduced by 27% and 31%, respectively (Fig. S2). These lower emissions resulted in a 25% reduction of the MEP impact, thus considerably decreasing the gap between the two systems (from 31 to 6%, as shown in Figure S2 of the Supplementary Materials). Accordingly, these results confirmed that the higher MEP impact of Case 1 was primarily dependent on the site conditions rather than the organic agronomic management.

Based on Figure 8, the systems had very different impacts also concerning the following ICs: ionizing radiation potential (IRP), terrestrial acidification (TAP), terrestrial ecotoxicity (TETP), freshwater ecotoxicity (FETP), marine ecotoxicity (METP), human carcinogenic toxicity (HTPc), mineral resource scarcity or surplus ore potential (SOP), fossil fuel scarcity (FFP), and water use (WCP). For instance, the impact of ionizing radiation potential (IRP) was greater in the conventional high-input system (Case 2) as a consequence of the higher emissions of radionuclides coming from diesel and fertilizer manufacturing and use. Similarly, terrestrial acidification (TAP) was much more intense for Case 2 due to the higher sulfur dioxide emissions from the production of fertilizers, pesticides, and diesel. The same processes were also responsible for the significant impact of the conventional high-input system, in terms of human carcinogenic toxicity (HTPc), by being very energy-intensive manufacturing processes. Similarly, terrestrial ecotoxicity (TETP) was particularly increased by the emissions of copper, vanadium, and zinc from the production of fertilizers and the ones from the application of herbicides. Also, marine and freshwater ecotoxicity impacts (METP, and FETP) were prompted by the release of herbicides, fungicides, and heavy metals into the different environmental compartments. The organic low-input system resulted to have also high potential for saving resources by minimally consuming mineral resources (SOP), oil (FFP), and tap water (WCP) compared to the conventional and high-input system. Accordingly, for Case 2, the production and use of external inputs, such as seeds, fertilizers, pesticides, and fuel, contributed to a relevant share of almost all the environmental impact categories.

3.3 Final considerations

The results of this article enable the authors to:

1. Provide insights into the methodological aspects of LCA application to cropping systems
2. Identify possible strategies for mitigating and/or improving the environmental profiles of the durum wheat production systems.

From a methodological point of view, the study has confirmed that *combined* models (between *product* and *system* approaches) considering the crop rotation effects are necessary when performing comparative LCAs between very different agricultural systems (Goglio et al. 2018). Indeed, in this study, the adjustment of the system boundaries at the crop rotation level through the accounting of inter-crop relations has allowed to represent the two systems in a more realistic and equitable way. Moreover, the combined approach allowed also to evaluate the influence of the CR effects directly in the environmental results, and thus to identify wide-ranging mitigation strategies, questioning the entire management of the cropping systems, and not only the main crop's cultivation.

Also, the authors recommend the use of multiple functional units to verify that results were as congruent as possible, despite more functions/perspectives being considered. In this study, the results obtained for the four functional units were found by the authors to be overall consistent with one another. It is well known, however, that this only happens sometimes, and that looking for trade-offs between different system dimensions often becomes crucial to provide truly feasible solutions to lower impacts.

Likewise, the authors suggest combining midpoint and endpoint impact assessment methods for the sake of more holistic environmental analyses. Thereby, the use of the endpoint method in this article permitted to perform a global evaluation and rating of the investigated systems; while the midpoint one allows to cover all the possible environmental impacts, including those that would have been neglected by the endpoint approach in deriving the damage indicators.

With regard to the mitigation strategies, the authors identified the following main ones for the organic low-input system:

- The enhancement of yield performances under organic and low-input farming
- The optimization of nitrogen provision from the leguminous crop.

The first task is crucial for the entire cereal organic sector, given that it currently faces the difficulty of using a high-input-based agriculture and needs more suitable genotypes.

In this sense, DW landraces and old varieties have the disadvantage of being less productive than commercial cultivars (Adhikari et al. 2022). They have, however, a broader genetic base which can be easily exploited to develop new genotypes characterized by higher productivity, adaptability to local conditions, and quality (Roselló et al. 2019; Nazco et al. 2012). Research on this subject has increased considerably over the last 20 years, demonstrating that the development of evolutionary populations (EP) from landraces is effective in improving yield and resistance to biotic and abiotic stresses (Bocci et al. 2020; Raggi et al. 2017; Döring et al. 2011). Efforts should be focused upon improving those two features, which are both highly relevant to eco-efficiency in low-input systems (Kulak et al. 2013).

The faba bean rotation was confirmed to be a valid option for the organic, low-input system by assuring the avoidance of using N fertilizers for DW cultivation. However, as discussed above, such a CR effect also translated into several impacts. This suggested the possibility of experimenting different uses of faba bean in the crop rotation, such as intercropping. In line with Agegnehu et al. (2008) and Xu et al. (2018), the intercropping of faba bean and wheat could increase total grain production, provide a diversity of products, stabilize yield over seasons, reduce economic and environmental risks common in monoculture systems, and, thereby, enhance sustainability. Especially, an increased grain yield during intercropping can be achieved due to an improved capacity of N supply and soil conservation, via intensification of the mineralization-immobilization turnover (Xu et al. 2018). Faba bean flour could also be added into the pasta formulation to increase its nutritional quality (Multari et al. 2015).

As far as the conventional high-input systems are concerned, high margins of improvement could be obtained, according to the authors, by:

- Shifting towards a more efficient rotational scheme
- Minimizing the use of external production inputs, such as purchased seeds, fertilizers, and pesticides
- Decreasing the intensity and frequency of soil tillage operations.

With regard to this point, replacing the bare fallow with a cover crop may help to control weeds, reduce nitrate leaching, and provide additional mulch, thus leading to multiple beneficial effects (Gabriel and Quemada 2011).

4 Conclusions

The study conducted attained the proposed goal of assessing and comparing the environmental performances of two very different DW cropping systems through LCA. Important differences were detected thanks to the adoption of some novel methodological choices, including i) the accounting for crop rotation effects through a new *combined* modelling approach; and ii) the use of multiple FUs, explicitly aligned with the main DW stakeholders' perspectives, including a qualitative one reflecting the interests of both farmers and processors.

The results highlighted that the low-input DW cropping system based on organic farming and local genotypes had a lower total environmental impact than the conventional and high-input one, regardless of the functional unit adopted. Considerable potential for environmental optimization was revealed for each investigated system. Accordingly, specific mitigation measures were proposed, such as implementing more efficient and well-designed crop rotations, less intensive soil tillage operations, and reduced use of fertilizers and agrochemicals. Regarding the organic sector, the study highlights the urgent need for projects involving breeders, farmers, processors, and food and environmental scientists to develop more productive, adaptable, and high-quality durum wheat varieties. In particular, an increase in productivity should be pursued by acting on both genetic resources and agronomic practices to minimize land use impacts. Moreover, to improve the representation of agroecological farming systems in LCAs, land use should be assessed using more comprehensive methods, possibly able to integrate the effects of land management on soil quality and biodiversity (Boschiero et al. 2023).

Finally, based on this study, the authors recommend combining modeling approaches, multiple functional units, and midpoint and endpoint assessment methods. These are, in fact, essential when performing comparative LCAs of cropping systems to get an accurate and holistic understanding of the leading environmental issues.

The authors will build upon results obtained in this study, along with those from Zingale et al. (2024) on the combined quality, energy, and environmental assessment of DW pasta cooking, to carry out further research aimed at: (i) evaluating how adopting the proposed improvements could lead to environmental benefits in DW farming systems; and (ii) accounting for the consumers' perspective through the use of a nutritional FU for cooked pasta. Doing so will make it possible to cover both the core and the down stream part of DW supply chain, thereby contributing to edvancing the specialized literature and knowledge in such an important research content area.

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Declarations

Ethics approval Not applicable.

Consent to participate Verbal informed consent was obtained prior to the interviews with farmers.

Consent for publication The authors affirm that the farmers participating in the study provided informed consent for the publication of the image in Figure 1 and information in Sect. 2.1 and 2.3.

Competing interests The authors declare no competing interests.

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