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Millets and sorghum as promising alternatives to maize for enhancing climate change adaptation strategies in the Mediterranean Basin

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ABSTRACT

Context: Climate change is increasingly requiring the adoption of both climate-resilient alternative crops and sustainable management practices. Millets and sorghum are increasingly recommended as alternatives to maize in addressing these issues, yet there are no studies comparing the environmental impacts of food-crop millets and sorghum with maize, under sustainable management in Mediterranean area.

Objective: The present study examined for the first time the environmental and economic impacts, as well as agronomic performances, of rainfed cultivated proso millet, sorghum and maize over a three-year period under challenging climatic conditions in Emilia-Romagna region, Italy.

Methods: Different kinds of trials were realized during three years of experimentation in one location in Ravenna province. The first trial aimed to compare proso millet, sorghum and maize agronomical performances and water use efficiency in a low-input system. The second trial aimed to compare soil fertility and biodiversity impacts of two different agronomical management systems (low-input and high input) for the summer crops previously described. Soil basic fertility parameters were monitored and ground dwelling arthropods were collected and analyzed using pitfall traps. The last trial of this study intended to evaluate the environmental and economic performances of the previous cereal crops cultivated in the low-input and high-input systems, applying the Life Cycle Assessment (LCA) and the Life Cycle Costing (LCC) methodologies.

Results: Both organic sorghum and millet showed high potential as viable summer-crop alternatives, not only to organic maize, based on yield, water use efficiency, disease tolerance and weed competition, but also to conventional maize, based on reduced environmental and economic impacts. Positive land impacts including improved beneficial arthropod abundances and preserved soil fertility were evident under organic management. In fact, the comparative LCA and LCC, carried out with primary data from conventionally cultivated maize and sorghum within central-north Italy and the organic experimental field under investigation, showed that the Global Warming and Eutrophication Potential, were comparable between the organically cultivated crops and significantly lower than conventional maize and sorghum.

Conclusions: The results highlighted the potential of sorghum and millet cultivation as rainfed summer-crop alternative to maize in climate-change context, especially in low-input agronomical systems. In particular, under rainfed, organic management over three years, proso millet yielded consistently.

Implications: Under the sustainable practices of the present study, proso millet outperformed maize for yield and WUE stability, as well as potential costs saved, related to the production amount per unit area and potential revenue.

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1. Introduction

Global warming, consisting of the increase in global temperatures primarily attributable to increasing atmospheric greenhouse gases (GHGs), is largely driven by human activities, including resource-intensive agricultural practices (Wang et al., 2018). Currently, the increase of GHGs concentration in atmosphere is the predominant driver of climate change, which is the long-term alteration in weather patterns (temperature, precipitation and wind patterns) over time (USGS, 2020). Climate change directly influences the quality and availability of both water and soil resources, impacting on the productivity of major cereal crops (Saxena et al., 2018). Based on current and past climatic trends, crop modelling studies have unanimously projected decreased future yields in varying regions of the globe for the major cereal crops (Lobell et al., 2011; Rosenzweig et al., 2014; Ray et al., 2015). Using the ensembles of the latest generation of crop and climate models, a 24 % decline in the global yield of one of the most susceptible crops, maize, was projected for 2099, with significant declines becoming apparent as early as 2030 (Jägermeyr et al., 2021). Mediterranean climate change, currently characterized by low and erratic precipitations, along with increasing temperatures, has been shown to compromise yield stability of all major cereal crops in Southern and Western Europe (Ray et al., 2015). Statistical data about maize cultivated area and grain production in Mediterranean area confirmed the cultivation crisis for this crop. Over a period of 20 years (from 2002 to 2022), the maize cultivated area and grain production decreased by approximately 26 % and 24 %, respectively, considering the countries included in the Northern Africa and Southern Europe areas (FAOSTAT, 2024). Given that climate change is inextricably linked to food security, these predictions highlight the necessity for mitigation and adaptation strategies in food production in coming decades (Jägermeyr et al., 2021). One such strategy advocates the use of alternative crops, such as millet and sorghum, which also have enormous potential for reducing the impact of agriculture on global warming (Saxena et al., 2018; Wang et al., 2018; Bvenura and Kambizi, 2022).

Compared to maize crop, millets and sorghum are less resource-intensive (requiring little or no input of fertilizer and water), can reduce GHGs emissions (lower carbon footprint), are able to grow in marginal regions (soils of poor structure, low fertility and low water holding capacity), are better adapted to withstand high radiation, inadequate and erratic rainfall, have shorter growth cycles and more stable yields (Awika, 2010; Saleh et al., 2013; Saxena et al., 2018; Wang et al., 2018; Mundia et al., 2019). As summer crops, millets and sorghum are also less susceptible to pest and disease in regions prone to adverse climatic conditions compared to maize (Bvenura and Kambizi, 2022; van Oosterom et al., 2021). In addition, compared to maize, millets can positively contribute in improving soil fertility, as demonstrated in previous studies (Rebonatti et al., 2023). Along with recent recommendations from the scientific community that these crops could be cultivated globally to mitigate food insecurity and agricultural impacts on global warming (Saleh et al., 2013; Wang et al., 2018), there has also been a renewed research interest in the innovation potential to address the current lack of development in millets and sorghum (Vital, 2018), specifically in developing countries (Mundia et al., 2019; Orr et al., 2020; Kane-Potaka et al., 2021; MacCarthy et al., 2021). However, interest in millets and sorghum as alternatives to major cereals is not necessarily limited only to developing countries (van Oosterom et al., 2021; Vital, 2018). In a recent study, for instance, proso millet was cultivated in Emilia Romagna to evaluate the potential adoption of this summer crop as a promising resilient alternative food crop to maize in the Mediterranean Basin (Ventura et al., 2022). The general increasing interests towards possible alternative crops, such as millets or sorghum, is also enhanced by many studies, which demonstrated their appealing characteristics as raw materials for both gluten free food production or feed sector (Moss and McSweeney, 2022; De Oliveira et al., 2022; Nematpour et al., 2021).

Aside from the selection of resilient crops, success in coping with climate necessities also the adoption of sustainable agricultural practices to reduce negative environmental impacts on the soil, air, water and biodiversity (Gava et al., 2018; Ventura et al., 2022). Climate change, together with monoculture farming and associated resource-intensive agricultural practices collectively increase GHG emissions (Tamburini et al., 2015; Gava et al., 2019; Saxena et al., 2018; Alhashim et al., 2021). Italy is typically characterized by intensive farming, supported by the use of large quantities of fertilizers, pesticides and irrigation, that contribute to the contamination of the soil and groundwater with various forms nitrogen (N) and phosphorus (P), as well as potentially toxic residues (Tamburini et al., 2015).

On one hand, intensive maize agroecosystems are known to negatively affect arthropod diversity (Chmelíková and Wolfrum, 2019; Norris et al., 2016). On the other hand, practices such as diversification and rotation are considered a promising way of improving agricultural ecosystems for biodiversity (McLaughlin and Mineau, 1995; Beillouin et al., 2021). Beneficial arthropod groups, for instance, are well known for responding to landscape- and local-level elements of farmland and agricultural management (Depalo et al., 2020; Burgio et al., 2015), with ground-dwelling arthropods being particularly influenced by crop type and diversification (Aguilera et al., 2020; Jowett et al., 2021). Many ground-dwelling arthropods are important providers of ecosystem services such as biological control. Ground beetles (Coleoptera: Carabidae), for example, are useful predators of both invertebrate pests (Lövei and Sunderland, 1996; Kromp, 1999) and weed seeds (Lami et al., 2020) and are also considered potential bioindicators of environmental quality and biodiversity (Rainio and Niemelä, 2003; Corcos et al., 2021). Another ground-dwelling arthropod group that is being increasingly considered important in conservation biological control of pests is represented by spiders (Araneae) (Michalko et al., 2019a,b). For these reasons, there is a huge interest in understanding the impact of management actions such as crop rotation on the assemblages of these arthropod taxa (Dunbar et al., 2016; Meyer et al., 2019).

The objective of European Life-CCA EU project, Growing REsilience AgriculTure (GREAT LIFE) is to face the effects of climate change on agricultural activities in Italy and as well as the European Mediterranean Basin, through the adoption of stress-resistant low-demanding crops, as well as the experimentation of rational rotation schemes and other sustainable agronomic practices. In fact, despite the potential of resilient low-demanding crops, aspects pertaining to sustainable agronomic practices have yet to be effectively evaluated.

Life-cycle assessment (LCA) has emerged as a dominant approach to assess the environmental impact of various crops and products across the world (Alhashim et al., 2021). From a recent meta-analysis conducted, commonly selected environmental impacts from agricultural practices include the global warming potential (GWP), the eutrophication potential (EP; fertilizer usage effects primarily on water) and acidification potential (AP; N-based emissions into the air) (Alhashim et al., 2021). Into this context, the Life Cycle Costing (LCC) can also be incorporated to integrate cost information, thereby creating a framework to address the overall sustainability of the agricultural production process (Tamburini et al., 2015;Gava et al., 2019). Considering that LCA is increasingly used, specifically in Europe, wheat and tomato represent the most well-studied crops (Alhashim et al., 2021), while more knowledge is needed for maize, sorghum and millet. Although LCA with LCC is promoted as an excellent tool in targeting environmental policy interventions in agri-food with respect to the UN 2030 Sustainable Development Goals (SDG) (Gava et al., 2019), of which SDG13 (climate action; preventing global warming) and SDG15 (life on land; preventing soil degradation and biodiversity loss) are of great interest, organic agriculture is often misrepresented (van der Werf et al., 2020). This misrepresentation is largely attributable to the use of a product-based and not land-based approach of the LCA, which also rarely considers aspects that agroecology aims to improve, including soil health, biodiversity and rational use of pesticides (van der Werf et al., 2020).

Emilia-Romagna is one of the leading agricultural regions in Italy. The dominant summer cereal cultivation in this region is maize, which was shown to decline in surface area by nearly 50 % between 2006 and 2021 (AGRI-Food Data Portal, 2022). These losses are partly attributable to the increased frequencies of both erratic and extreme rainfall patterns in Emilia-Romagna in recent years (Persiano et al., 2020). Within the framework of the GREAT LIFE project, the present study was aimed at evaluating the performance of the proso millet (*Panicum miliaceum* L.), sorghum (*Sorghum bicolor* L. Moench) and maize (*Zea mays* L.) in a rotation scheme, under sustainable (organic) agronomic management practices, on a rainfed farm in the Emilia-Romagna region, over a period of three years (Fig. 1). A multi-disciplinary approach was undertaken which included investigating soil properties and beneficial arthropod diversity from the sustainable cultivation of the two alternative crops and maize, in comparison to maize under conventional agriculture. Finally, a LCA, including an associated LCC analysis, was conducted to firstly compare the environmental and cost impacts of the three crops under organic conditions and secondly to compare the environmental and cost impacts of organic sorghum and maize to that of conventional sorghum and maize, respectively.

2. Materials and Methods

The present study includes the results of different field trials.

The first field trial's objective was to compare proso millet, sorghum and maize agronomical performances for water use efficiency under low-input management system. The experiment was conducted during three years (2019–2021) in one location, in Ravenna province. Following the crop rotation scheme described in the following Section 2.1, proso millet, sorghum and maize have been cultivated every year in 100 m^2 plots, following a randomized complete block design, with three replicates for each crop.

The second trial aimed to compare soil fertility and biodiversity impacts of two different agronomical management systems (low-input and high input), applied to different summer crops, previously described. The experimentation was realized in the same location and during the same three years of the previous trial, in Ravenna province. Soil basic fertility parameters were monitored, and ground dwelling arthropods were collected and analyzed using pitfall traps. For this experiment, following a completely randomized design, three replicates for soil and arthropods sampling were collected in two different (organic and conventional management) fields every year, as detailed in Section

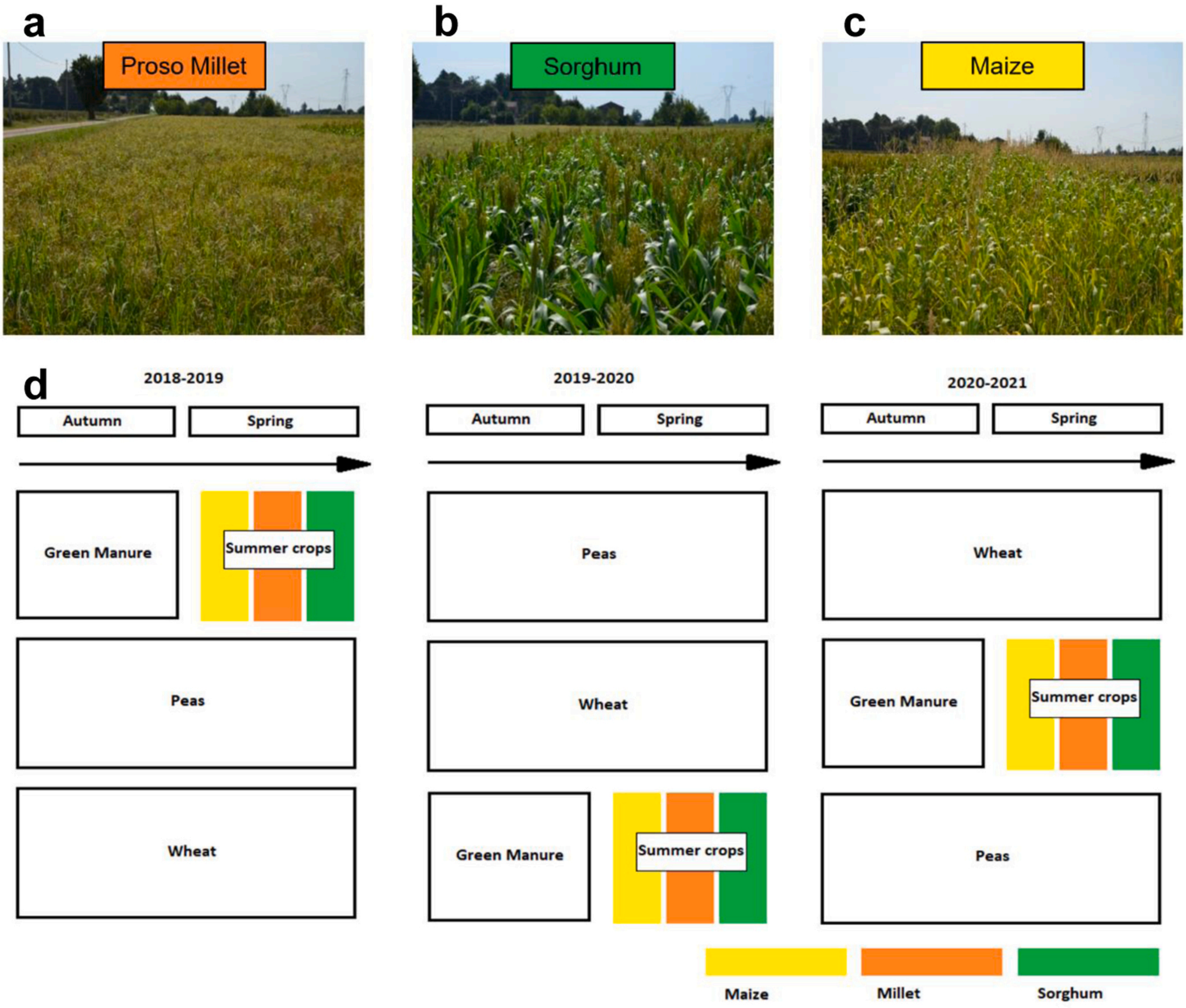

Fig. 1. Proso millet (**a**), sorghum (**b**) and maize (**c**) cultivated as part of a rotation scheme (**d**) under organic management over a three-year period in Emilia-Romagna region (Italy).

2.4.

The last trial of this study intended to evaluate the environmental and economic performances of the previously mentioned summer cereal crops (proso millet, sorghum and maize), cultivated in low-input and high-input systems, applying the LCA and the LCC methodologies. For these LCA and LCC elaborations, collected information from the first field experiment of this research (alternative summer crops comparison) were considered as input data for the "low-input" systems, while information obtained from 25 conventional farms located in central-north Italy were employed as input data for the "high input" systems.

2.1. Experimental site locations, seed material and agronomic management

The study included an organic and a conventional field. The organic field (Villa Masini) was located near Ravenna (44°15’59.5"N 12°07’46.5"E) in Emilia-Romagna region, Italy, and was involved in the agronomical evaluation trial of different summer cereal performances in a low-input system. The summer crops of interest were proso millet, sorghum and maize respectively, that were cultivated as part of a rotation scheme over a period of three years, from 2019 to 2021 (Fig. 1). The rotation scheme was comprised of a succession of pea, wheat and summer crops, these latter preceded by the cultivation of an autumn-winter cover crop, incorporated in the soil at the end of winter season, obtaining a green manuring. Three plots, each of 1000 m^2 were, respectively, designated for the cultivation of wheat, pea and green manure (a mixture of ryegrass, clover and vetch) that were sown annually in the autumn, preceding summer crops. The sowing density was 180 kg ha^{-1}, 250 kg ha^{-1} and 80 kg ha^{-1} for wheat, pea and the green manure, respectively. At the end of winter, the green manure crop was mowed down and after some days incorporated into the soil as a fertilizer source, with a disk harrow. Later, millet, sorghum and maize were sown in separate subfields (Fig. 1).

The location of the field under conventional management was near Villa Masini, close to Ravenna (44°16’01.2"N 12°07’41.7"E) and was involved in the soil fertility and biodiversity evaluation trial, in comparison with the organic field previously described. Conventional maize was cultivated in 2019 and 2020 over a surface area of 5000 m^2, followed by conventional wheat in 2021.

Proso millet seeds (Pearly Millet Blond variety) were purchased from the Arcoiris seed company (Arcoiris srl, Modena, Italy). The sorghum seeds (sorghum hybrid "Felsina") were purchased from the Società Italiana Sementi company (S.I.S, Bologna, Italy). Early-medium maturity, more water-stress tolerant maize hybrid seeds ("MAS 37.H", FAO Class 300) were obtained from Mas Seeds (Mas Seeds, Haut-Mauco, France) for cultivation in the organic management system. The same maize hybrid seeds were sown in the conventional field.

The soil type of the organic field was "silt loam", with a sediment granulometric ratio of 24:58:18 for clay:silt:sand, whereas the soil type of the nearby conventional field was "silty clay loam", with a sediment granulometric ratio of 28:61:11 for clay:silt:sand (Agriparadigma laboratories, https://www.agriparadigma.it/). Following the FAO World Reference Base for Soil Resources (IUSS Working Group WRB, 2015), both sites were classified as Cambisols. The soil fertility attributes analyzed during the three years trial in the organic and conventional fields are reported in Table 1.

Details pertaining to the sowing and harvesting dates, seed density at sowing, sowing depth and inter-row distance for the organically cultivated millet, sorghum and maize, as well as the conventional maize and wheat, are provided in Table 2. In accordance with organic management practices, the millet, sorghum and maize in rotation were not treated with synthetic herbicides (Table 2). Instead, prior to sowing, the "false" seedbed technique was used. Basically, a regular seedbed was prepared before the crops sowing time but instead of sowing the crops immediately, weeds were allowed to germinate and after one week the soil was tilled again, before sowing the actual crops. Weeding was also performed mechanically (inter-row cultivation) in both the organic and conventional fields during crop development. In contrast to the conventional field where synthetic fertilizers were applied (Table 2), green manure was the exclusive fertilizer source in the organic rotation field.

Soil management prior to sowing was ploughing (deep tillage) in the conventional plot, whereas the conservative practice of ripping (minimum tillage) was performed in the organic field. Harrowing, a minimal tillage technique, was then performed in both experimental fields as a secondary conservative practice to provide a finer soil preparation. The organic trial was rainfed, whereas supplementary irrigation was supplied to the conventional plot (Table 2).

Organic field (ORG); Conventional field (CON); Dry Matter (DM)

2.2. Meteorological Data and Water Balance

Meteorological data (maximum, minimum, average daily air temperature and daily precipitation) over the three-year period was monitored by the ARPAE-Simc agrometeorological station of San Pietro in Vincoli, which was the closest (distance of 4 km) to the experimental fields. To compensate for missing rainfall data in 2021 at San Pietro in Vincoli, data was obtained from the ARPAE-Simc agrometeorological station of Coccolia, which was similarly positioned close to the experimental site.

The calculation of the water balance in the organic field was performed as described in Ventura et al. (2022). Supplementary information was obtained from the IRRIFRAME portal for calculations of crop water balance. The IRRIFRAME portal (https://www.irriframe.it/Irriframe) is an irrigation advisory service for farm water management based on a water balance model, which takes into account the soil–-plant–atmosphere continuum, including soil water balance, plant development and atmospheric thermal regime, rainfall, and evaporative demand (Ventura et al., 2022). For each crop, the water balance was calculated in order to relate yield to water consumption (water use efficiency, WUE).

2.3. Agronomic Performance

To assess the agronomic performance of organic proso millet, sorghum and maize at Villa Masini, prior to harvesting, three random replicate sampling areas of 1 m^2 for each crop were evaluated. The

Table 1
Soil characteristics monitored during the three years trial in the organic and conventional field. Soil samples have been collected in the 0–40 cm depth soil layer.

Experimental fields	ORG			CON		
Soil texture	**Clay**	**Silt**	**Sand**	**Clay**	**Silt**	**Sand**
	24	58	18	28	61	11
Soil fertility attributes	**2019**	**2020**	**2021**	**2019**	**2020**	**2021**
Organic matter (g kg^{-1} DM)	16.33	15.78	15.33	12.33	10.00	8.83
pH	7.73	8.14	8.01	8.07	8.23	8.05
Total N (g kg^{-1} DM)	0.66	0.61	0.82	0.65	0.61	0.51
Assimilable P (mg kg^{-1} DM)	<9	11.50	11.25	<9	<9	<9
Assimilable K (mg kg^{-1} DM)	158.00	220.44	175.67	146.00	123.67	185.00

Table 2
Agronomic management practices of the organic cultivation system for proso millet, sorghum and maize and the conventional cultivation system for maize and wheat, during a three-year period (2019–2021).

	Organic			Conventional		
Crop Type	Proso Millet	Sorghum	Maize	Maize	Maize	Wheat
Sowing date	17/04/2019 27/04/2020 22/04/2021	17/04/2019 27/04/2020 22/04/2021	17/04/2019 27/04/2020 22/04/2021	20/04/2019	30/04/2020	18/10/2021
Soil management	Ripping + harrowing	Ripping + harrowing	Ripping + harrowing	Ploughing + harrowing	Ploughing + harrowing	Ploughing + harrowing
Sowing depth	2 cm	3 cm	4 cm	4 cm	4 cm	2.5 cm
Inter-row D	8 cm	70 cm	70 cm	70 cm	70 cm	8 cm
Seed density	40 kg ha^{-1}	15 kg ha^{-1}	80.000 seeds ha^{-1}	80.000 seeds ha^{-1}	80.000 seeds ha^{-1}	200 kg ha^{-1}
Fertilization management	Green manure	Green manure	Green manure	Urea (46 %) 600 kg ha^{-1} Single-super P (19 %) 300 kg ha^{-1}	Urea (46 %) 600 kg ha^{-1}	Urea (46 %) 270 kg ha^{-1} Single-super P (19 %) 150 kg ha^{-1}
Weeding management	Pre-seeding: False seedbed, Post-emergence: flex-tine finger weeder	Pre-seeding: False seedbed, Post-emergence: inter-row cultivation	Pre-seeding: False seedbed, Post-emergence: inter-row cultivation	Pre-seeding: chemical Post-emergence: chemical + mechanical	Pre-seeding: chemical Post-emergence chemical + mechanical	Pre-seeding: none Post-emergence: chemical
Irrigation	none	none	none	100 mm	180 mm	None
Harvest date	01/08/2019 12/08/2020 13/08/2021	29/08/2019 07/09/2020 03/09/2021	29/08/2019 07/09/2020 03/09/2021	10/09/2019	18/09/2020	05/07/2021

Inter-row distance (D); Supplementary (S) Irrigation.

parameters measured were plant height (measured on 5 plants at the panicle insertion), panicle length and weight of grains per panicle (measured on 5 panicles), panicle number per area, ground coverage, weed infestation, pathogen incidence and pathogen severity. Ground coverage and weed presence were measured through visual analysis of the soil surface, where the percentage of ground cover and weed presence represented the ratio of crop vegetation and weed presence, respectively, with bare soil (with 0 % = bare soil and 100 % = soil not visible due to complete plant coverage). Disease ratings were calculated using a descriptive assessment scale with different classes of scale ratings (i.e. 0–10), in which each rating corresponded to pathogen percentage or pathogen severity over the surface area of tissues under investigation. The scoring scale adopted was as follows: 0 = no infection, 1 = 1–10 %, 2 = 11–20 %, 3 = 21–30 %, 4 = 31–40 %, 5 = 41–50 %, 6 = 51–60 %, 7 = 61–70 %, 8 = 71–80 %, 9 = 81–90 % and 10 = 91–100 %. Thereafter, at harvest, the same three replicate areas for each crop were harvested to quantify grain yield and WUE. Grain yield for WUE calculation was expressed as grain kg m^{-2}, at 0 % grain humidity (determined after grain drying in an oven at 65°C until constant weight of sample was reached).

2.4. Soil characteristics and arthropod biodiversity between the organic and conventional cultivation systems

Given the importance of these aspects, soil parameters, arthropod abundance and diversity were analyzed. Soil analyses (organic matter content, pH, and mineral components) were carried out by Agriparadigma laboratories (https://www.agriparadigma.it/), following official method protocols. Soil organic carbon and total nitrogen were determined on air dried, finely ground soil samples with an elemental analyzer (CHNS-O Elemental Analyzer 1110, Thermo Scientific GmbH, Dreieich, Germany). Soil organic matter content was estimated by multiplying the carbon content by the standard coefficient 1.724. Soil available P (P_{Olsen}) was determined following the method reported by Olsen et al. (1954). Plant-available potassium is measured by analyzing an ammonium acetate extract of soil samples with an atomic absorption spectrometer set on emission mode at 766.5 nm, following the method reported by Merwin and Peech (1951).Ground dwelling arthropods were collected using pitfall traps. Each trap consisted of two plastic cups (600 ml, 10 cm in diameter), positioned at a distance of 1 m from each other. The two cups were placed in the soil, flush with the soil surface, and were connected using a plastic barrier (height of 10 cm) to facilitate the capture of the arthropods in the space between the cups. The cups were filled with 200 ml 40 % propylene glycol. Once a month, from June to August of each sampling year, three pitfall traps were placed in each organic and conventional field (at a distance of 30 m from each other and at least 30 m from the field edge). The traps were left for a period of 7 days at a time, with the exception of August 2020, where traps were active for 11 days.

The number of individuals of the four most abundant arthropod groups, which were ground beetles, spiders, crickets and grasshoppers (Orthoptera) and harvestmen (Opiliones), were counted. Given the abundance of ground beetles and their importance as biodiversity indicators (Magagnoli et al., 2018), they were identified visually to the species level. For each arthropod group in each field, the activity density in the individual years and in the overall study was also calculated, with activity density representing the mean number of individuals captured by a single trap over 10 days of activation (Thomas et al., 2006).

2.5. Life Cycle Assessment (LCA) analysis and Life Cycle Costing (LCC)

A LCA was performed based on the most commonly used formalized methods, namely ISO 14040:2006 (ISO 14040, 2006), ISO 14044:2006 (ISO 14044, 2006) and also Product Category Rules for "Arable and Vegetable Crops"(PCR 07, 2020), considered "a suitable tool for sustainability assessment" in the agricultural sector (Alhashim et al., 2021). The ISO series are comprised of four principal phases: 1) the definition of the goal and scope of the LCA; 2) the life cycle inventory analysis phase; 3) the life cycle impact assessment phase, and 4) the life cycle interpretation phase. The LCC was incorporated to integrate cost information, thereby creating a framework to address the overall sustainability of the agricultural production process. The LCC was developed on the basis of the official guidelines from Davis Langdon Management Consulting (2007) and ISO 14008:2019 (ISO 14008, 2019), here adapted to agriculture sector

2.5.1. The definition of the goal and scope

The goal of the present research was to determine how different inputs and outputs impacted on environmental and economic indicators, to evaluate the environmental and economic performances of the crops cultivated in the sustainable system, and to identify the most critical hotspots and how they differ from the performances linked to cultivation in conventional systems. Within the scope, the system boundaries were set from the *cradle* (sowing of maize, millet and sorghum) to the *farm-gate* (farm activities to harvest). The boundaries included all agricultural production practices (energy/fuel/water resources and materials). For the objective of investigating land impacts and for LCC, the functional unit selected was 1 ha. Hence, all resources and impacts incurred were calculated based on 1 ha of land. Impact results were also expressed as 1 kg of product for comparative purposes. The geographical region was Emilia-Romagna for the multi-year analysis (2019–2021) for the sustainable organic cultivation (reduced tillage, conservation of organic matter, rotations, use of green manure) of millet, sorghum and maize. The geographical region for the comparison between organic and conventional management included central-north Italy. The organic maize and sorghum data (average of the previously described three years agronomical trial) were compared with the conventional maize and sorghum data, collected from 25 Italian farms in 2020.

2.5.2. *The life cycle inventory analysis*

The life cycle inventory is comprised of the sum total of the contributions of the inputs and outputs, in and out of the production system, including raw resources or materials, energy by type, water, and emissions to air, water and land by specific substances. In the preset study, the inputs and outputs originated from real farm data, supplemented with questionnaires containing sections regarding the different crops and agronomic practices by the farmers from the organic Villa Masini farm, as well as the 25 conventional maize and conventional sorghum farms. Information was compiled within a web-based data collection tool developed by the GREAT LIFE project. Inputs consisted different item for the conventional and organic system. In particular, the analysis included as inputs: seed material (including green manure sources), organic fertilizers (sewage, 3 % N granulite), synthetic fertilizers of various mineral N, P and sulfur (S) sources, protection (herbicides, insecticides and fungicides) and water inputs, energy sources for seed drying and agricultural machinery operations (harrowing, ploughing, sowing, irrigation/fertilization/protection sprayers, harvesters). Labor was included in the inventory specifically for the cost impacts of agricultural operations. In the present study the outputs were focused on the emissions into the air and water (CO_2, N_2O, CH_4, NO_x, NH_3, NH_4, PO_4, P_2O_5, SO_2) from agricultural machinery operations (the various types of energy input sources), as well as mineral fertilizers and protection sources.

2.5.3. *Life cycle impact assessment phase*

The life cycle impact assessment is used to evaluate the potential environmental impacts of the product based on the life cycle inventory. In the present study, environmental impacts were limited to the agricultural practices. The impact assessment selected was the ISO 14040:2006 and ISO 14044:2006 classification method, with different environmental impact categories. The indicator impact categories selected in the present were GWP (expressed in equivalent mass of carbon dioxide [Kg CO_2-eq]), the AP (expressed in equivalent mass of sulfur dioxide [Kg SO_2-eq]) and the EP (expressed in equivalent mass of phosphate [Kg PO_4-eq], respectively. Whereas the GWP is representative of emissions released into the air, the EP and AP are represented by emissions released into fresh water sources and to a lesser extent, the air. For the LCC and for each crop, costs were accounted for the same input categories of LCA elaborations, previously mentioned. The environmental and cost impact factors used for each inventory were derived from the LCA database Ecoinvent 3, Agribalyse 3.0, Agrifootprint (Nemecek et al., 2007). The calculations for land-based (ha^{-1}) environmental impacts are reported in Table 3. The product-based (kg^{-1}) impact calculation was realized dividing the land-based impacts for the specific crop yield (kg ha-1).

2.6. *Statistical analysis*

To perform ANOVA analysis for comparing agronomical results of the different crop species and soil characteristics of the organic and conventional trial, data normal distribution and homoscedasticity were verified for each variable with Shapiro–Wilk and Levene tests, respectively, with $p = 0.05$. When data did not meet the normal distribution assumption for ANOVA, data transformation were attempted and tests were recalculated. Tukey's post-hoc test was employed to separate means ($p = 0.05$). When data were normally distributed but not homoscedastic, the non-parametric Welch test was performed, and the Games-Howell test was used to separate the means, if the Welch test revealed significant differences ($p = 0.05$). All the statistical elaborations were performed with SPSS software Version 25.0 (Armonk, NY: IBM Corp.).

As for arthropod data, the activity density in the individual years and in the overall study was calculated for each group, with activity density (Thomas et al., 2006) representing the mean number of individuals captured by a single trap over 10 days of activation. Given the abundance of ground beetles and their importance as biodiversity indicators, they were identified visually to the species level. The number of ground beetle species and their Shannon and Evenness diversity indices (Magurran, 1988) in each field and year, as well as in the overall study, respectively, were calculated using Past v4.09. We calculated the overall abundance of each individual ground beetle species in the conventional and organic fields at each of the 9 sampling days (3 dates for 3 years) and used the data to compare the community composition between the two fields. This was achieved visually with a Nonmetric MultiDimensional Scaling (NMDS) plot (Minchin, 1987) and further tested with an analysis of similarities (ANOSIM) (Clarke, 1993) in both cases using Bray-Curtis distance (Bray and Curtis, 1957). In order to verify whether the sampling effort was adequate for the estimation of ground beetle diversity, we also

Table 3
Indicators algorithms adopted for the LCA elaborations. The specific environmental and cost impact factors, for each input category, were derived from the LCA database Ecoinvent 3, Agribalyse 3.0, Agrifootprint.

Inputs	Algorithm (for 1ha)	Indicator impact categories
Agricultural operation	$\sum_{k=agricultural\ operations}^{n} intervention\ number \times impact\ factor\ of\ the\ operation\ K$	all
Seeds	$Spread\ amount \times impact\ factor\ of\ that\ seed$	all
Phytochemicals products	$\sum_{k=phytochemicals}^{n} spread\ amount \times impact\ factor\ of\ the\ phytochemical\ K$	all
Production of synthetic fertilizers	$\sum_{k=synthetic\ fertilizer}^{n} spread\ amount \times impact\ factor\ of\ the\ only\ production\ of\ a\ fertilizer\ K$	GWP
Emissions of synthetic fertilizers	$\sum_{k=synthetic\ fertilizer}^{n} spread\ amount \times impact\ factor\ of\ the\ only\ emissions\ of\ a\ fertilizer\ K$	GWP
Synthetic fertilizers	$\sum_{k=synthetic\ fertilizer}^{n} spread\ amount \times impact\ factor\ of\ the\ fertilizer\ K$	All except for GWP
Organic fertilizers	$\sum_{k=organic\ fertilizer}^{n} spread\ amount \times impact\ factor\ of\ the\ organic\ fertilizer\ K$	all
Grain drying	$Energy\ consumption\ (Kwh\ or\ liters/quintals) \times impact\ factor\ of\ that\ energy\ type \times harvested\ grain\ (quintals/ha)$	all
Labor	$Internal\ labor\ hours\ spent\ for\ the\ crop\ cultivation \times cost\ per\ hour$	Direct costs

Global Warming Potential (GWP)

built species rarefaction curves (Chiarucci et al., 2008) in which each individual pitfall trap in each individual round was considered as a sampling unit. The NMDS, ANOSIM and rarefaction analyses were carried out using the “vegan” v2.5–6 package (Oksanen et al., 2019) in R 3.6.2 (R Core Team, 2018).

3. Results

Conditions compatible with climate change predicted effects were evident from the meteorological data for the 2019–2021 period (Ventura et al., 2022). Briefly, compared to the average precipitation (231 mm) over the summer season for the previous 30 years, 2019 was distinguishable by excess precipitations (310 mm), mainly concentrated in the second half of May, whereas both 2020 and 2021 were dry years, with 160 mm and 120 mm of precipitations during the vegetation season, respectively. Moreover, frequent heat wave events were reported in both 2019 and 2021 (Ventura et al., 2022). 2021 had also shown overall higher temperatures during June and July.

3.1. Agronomic performance of organically cultivated proso millet, sorghum and maize

The average agronomic performances of proso millet, sorghum and maize over the three-year period cultivated in the organic field are shown in Table 4. Given that the crops were different, with different responses to climate, an important objective was to examine the variability of yield related parameters over the three-year period. Proso millet yield remained stable around 3.28 t ha^{-1}, averagely, exceeding those of the Mediterranean basin over the same period (FOASTAT 2021), with 0.10 t ha^{-1}of standard error (Table 4). In 2019 the sorghum yield was 7.3 t ha^{-1}, comparable to the national average of 6.9 t ha^{-1} (FOASTAT, 2021), with yield declining in 2020–2021 under water scarcity regime. It is still notable that 2021 yield was 4.71 t ha^{-1}, which is nearly twice as much it was harvested in 2020 (2.51 t ha^{-1}), even though precipitation in 2021 were the lowest of the three growing seasons. As regards to maize, average yield (3.13 t ha^{-1}) was substantially lower than the average national of 10 t ha^{-1} under predominantly irrigated agricultural practices (FOASTAT, 2021). Grain panicle values of the three crops reflect what occurred with crop yields: millet had a narrow level of variation, sorghum had a wider variation, and maize the highest.

Table 4
Average agronomic performances of proso millet, sorghum and maize under sustainable organic management practices in Emilia-Romagna, Italy, over the three-year experimental period (2019–2021), from the first trial of the present research.

Crop	Panicles (number m^{-2})	Grain per panicle (g)	Yield (t ha^{-1})
Proso millet variety	207.34 ± 53.34 a	2.88 ± 0.20c	3.28 ± 0.10 ns
Sorghum hybrid	20.56 ± 5.57 b	25.64 ± 7.48 b	4.17 ± 1.69 ns
Maize hybrid	6.67 ± 2.27 c	43.38 ± 10.40 a	3.13 ± 1.44 ns
	Grain (as dry matter) (kg m^{-2})	Water consumption (m^3 m^{-2})	Water Use Efficiency (kg m^{-3})
Proso millet variety	0.29 ± 0,02 ns	0.15 ± 0.01 ns	1.87 ± 0.03 ns
Sorghum hybrid	0.38 ± 0.14 ns	0.17 ± 0.03 ns	2.26 ± 0.40 ns
Maize hybrid	0.28 ± 0.28 ns	0.18 ± 0.03 ns	1.30 ± 1.30 ns
	Crop cover (%)	Weed cover (%)	Plant height (cm)
Proso millet variety	73.33 ± 10.18 a	20.00 ± 5.36 b	103.56 ± 6.85 b
Sorghum hybrid	65.56 ± 12.52 a	25.56 ± 9.09 b	113.47 ± 10.65 ab
Maize hybrid	20.56 ± 0.56 b	76.67 ± 7.64 a	133.13 ± 10.76 a
	Pathogen incidence (0–10)	Pathogen severity (0–10)	Lodging (%)
Proso millet variety	0.22 ± 0.11 b	0.00 ± 0.00 b	0.00 ± 0.00
Sorghum hybrid	2.11 ± 0.11 a	0.56 ± 0.29 ab	0.00 ± 0.00
Maize hybrid	2.00 ± 1.68 a	2.33 ± 1.68 a	0.00 ± 0.00

A one-way ANOVA and Tukey’s test results are presented with different letters (a–c), denoting significant differences between the crops at *** $P \leq 0.001$. “ns” is not significant

The highest WUE was observed for sorghum due to the highest average yield, and its variability of reflects that of yield. Maize showed the lowest WUE value, with the highest variability, but also the highest water consumption value. Millet has lower WUE than sorghum, but more stables within the growing seasons and with the lowest water consumption value (0.15 m^{3}m^{-2}).

Crop soil coverage and weed soil coverage percentages show no statistically significant differences between millet and sorghum, while maize performances were substantially lower. From the disease ratings presented (Table 4), maize higher and more variable incidence and severity, whilst on millet they were negligible; sorghum showed an intermediate condition, there was no statistical difference with maize, regarding incidence, whether pathogen severity on sorghum (0.56 ab) has shown no difference from millet (0.00 b) and from maize (2.33 a). No lodging was registered in the three years of the study.

3.2. Land-based impacts on the environment: soil parameters

Soil analyses results regarding organic matter, total nitrogen and available potassium are shown in Fig. 2. Phosphorous (P) was often reported to be under detection threshold (<9 mg kg^{-1}). pH was not significantly different between the organic and conventional sites and ranged from slight to moderately alkaline, from 7.73 to 8.26. These pH values could have been determined by high Calcium content in the soil, that could have also limited the availability of P, potentially bonded in calcium-phosphate compounds. The higher soil C content under organic management is reflected in the organic matter content, which was significantly higher than in the conventional field ($P \leq 0.001$) (Fig. 2a). In organic management, the organic matter content ranged from 16.33 g kg^{-1} DM in 2019–15.33 g kg^{-1} DM in 2021, resulting in no significant difference. In conventional management, the organic matter content was 12.33 g kg^{-1} DM in 2019, and in 2021 it was significantly lower (8.83 g kg^{-1} DM). The average organic matter content of the organic system, at the end of the experiment, was 15.34 g kg^{-1}, compared to 9.00 g kg^{-1} of the conventional system.

The overall total N content of the soils is shown in Fig. 2b. No significant difference was reported between the conventional and biological systems. In contrast, similar minimal variation in the soil N content were associated with exogenously added N, contributing to greater emissions (see Section 3.4). Similarly, the assimilable K under organic cultivation, in which no K fertilizers were added, was comparable to the conventional system (Fig. 2c).

3.3. Land-based impacts on the environment: arthropod abundance, activity density and diversity

Arthropod abundance and diversity for the organic and conventional fields are shown in Fig. 3 and Table 5. The activity density of the three most abundant groups (Carabidae, Orthoptera, Araneae) fluctuated between the sampling years, but both ground beetles and spiders (the most important biological control agents) they were constantly higher in the organic field if compared with the conventional field. In the case of orthopterans, the difference between the two fields was less marked and in favor of conventional rotation. Opiliones were very scarce, especially during the first two years, and overall more abundant in the organic field.

Carabids diversity was analyzed in detail, considering them the primary target group, due to their well-known taxonomy, high susceptibility to anthropic stresses (Magagnoli et al., 2018) and higher

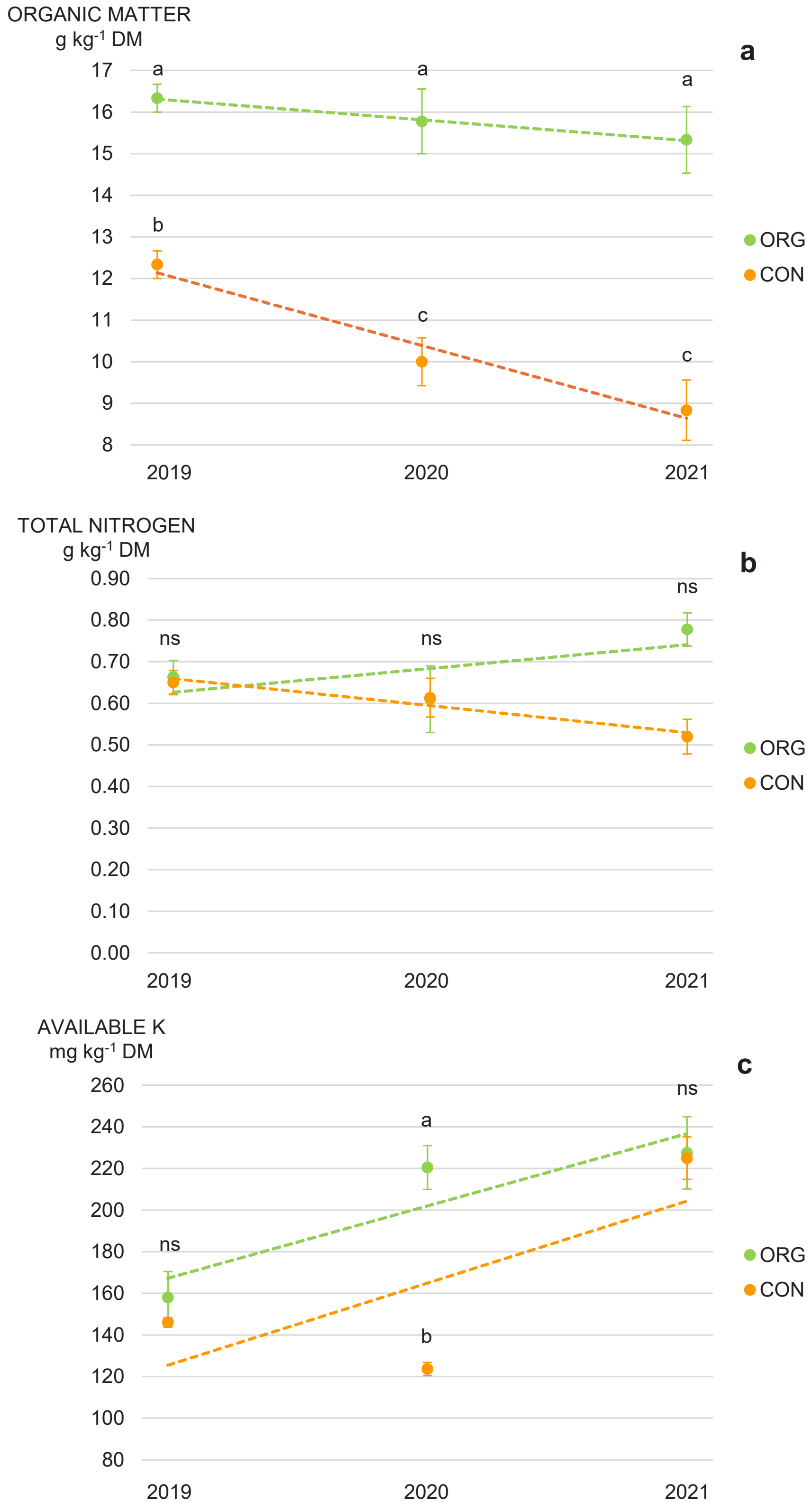

Fig. 2. Soil organic matter (**a**), total nitrogen (**b**) and assimilable potassium (**c**) in the organic (ORG) and conventional (CON) field between the end of the first agronomical season (September 2019) and after the final harvest in September 2021. "DM": Dry matter. The values at the first sampling time and at the final sampling time have been statistically analyzed as reported in Material and Methods section; different letters (a–c) denoting significant differences between the fields at *** $P \leq 0.001$. "ns" is not significant.

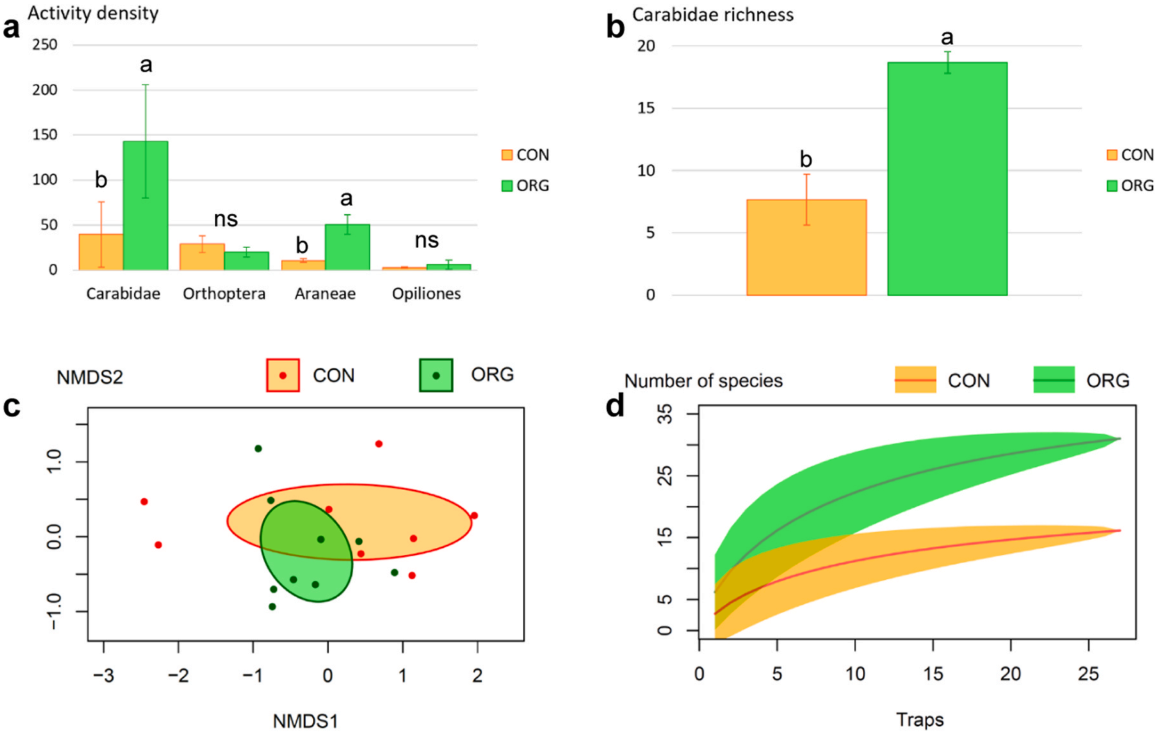

Fig. 3. Arthropod activity density (**a**) for the organic (ORG) and conventional (CON) fields between 2019 and 2021. Carabidae (ground beetle) richness (**b**) between the ORG and CON fields between 2019 and 2021. The histograms show the averages and standard errors for the three years trial. Different letters (a–b) denoting significant differences between the ORG and CON fields at *** $P \leq 0.001$. “ns” is not significant difference. Ordination plot based on Nonmetric Multi-Dimensional Scaling (NMDS) comparing ground beetle community composition between the maize CON and the ORG (rotation) field (**c**). Each dot is a sampling round in one of the fields. Ellipses indicate 95 % intervals of confidence. No difference in community composition between the two fields was evident using Bray-Curtis distance, used in the NMDS plot. The rarefaction curves (**d**) based on 1000 randomizations for the ground beetles sampled in the ORG rotation and maize CON fields.

Table 5
Abundance and activity density over 10 days of ground beetles (Carabidae), crickets and grasshoppers (Orthoptera), spiders (Araneae) and harvestmen (Opiliones) in the maize and rotation fields.

		2019		**2020**		**2021**		**Total**	
		Maize	**Rotation**	**Maize**	**Rotation**	**Maize**	**Rotation**	**Maize**	**Rotation**
Carabidae	**Abundance**	23	1155	844	1699	20	122	887	2976
	Activity density 10d	3.7	183.3	112.5	226.5	3.2	19.4	44.1	148.1
Orthoptera	**Abundance**	206	182	322	161	71	62	599	405
	Activity density 10d	32.7	28.9	42.9	21.5	11.3	9.8	29.8	20.1
Araneae	**Abundance**	76	255	51	542	84	248	211	1045
	Activity density 10d	12.1	40.5	6.8	72.3	13.3	39.4	10.5	52.0
Opiliones	**Abundance**	14	5	14	11	29	103	57	119
	Activity density 10d	2.2	0.8	1.9	1.5	4.6	16.3	2.8	5.9
Carabidae	**Species richness**	8	19	11	17	4	20	16	31
Carabidae	**Shannon_H**	2.06	1.01	0.97	0.91	0.87	2.40	1.09	1.09
Carabidae	**Evenness_eˆH/S**	0.98	0.15	0.24	0.14	0.60	0.55	0.19	0.10

In the bottom part of the table species richness, Shannon-Weaver and Evenness diversity indices for ground beetles in the maize and rotation fields are reported. Metrics were calculated for each individual year and for the entire dataset

abundance in the present experiment. As for Carabidae diversity, the organic field hosted a higher number of species (31 vs. 16 species over a total of 32 found across the entire study – Fig. 3b), including one record of the infrequently observed in farmlands (Allegro and Cristaldi, 2016) *Zuphium olens* (P. Rossi). The shape of the rarefaction curves (Fig. 3d) confirming that the sampling effort adequately detected the diversity of ground beetles in both fields. Despite these differences, the ground beetle community composition was not significantly different between the two fields, as evidenced by both the ANOSIM statistic ($R = 0.07$; p-value $= 0.15$) and the NMDS plot (Fig. 3c).

3.4. LCA and LCC analysis over the three-year period for organically-cultivated proso millet, sorghum and maize, and between organic and conventional sorghum and maize

The comparison of the land-based output impacts of organically-cultivated millet, sorghum and maize over the three-year period is shown in Table 6. Given that the same agronomic practices were implemented, the GWP, EP and AP impacts per hectare were comparable between the three crops. The average output data for the organically-cultivated maize and sorghum was then compared to the 2020 data collected from 25 conventional maize and sorghum farms in the geographical area (Table 6). A comparison between millet was not made, due to the lack of millet cultivation in Italy (FOASTAT, 2021).

Table 6
Life cycle analysis (LCA) showing the contribution to global warming potential (GWP), eutrophication potential (EP) and acidification potential (AP) outputs expressed on a land-based approach (ha) for organic proso millet, sorghum and maize over a 3-year period (2019–2021).

Indicator		Proso Millet			Sorghum			Maize		
		2019	2020	2021	2019	2020	2021	2019	2020	2021
GWP ha^{-1}	kgCo$_2$eq	247.88	288.76	258.74	259.39	298.69	245.17	249.12	351.35	272.54
EP ha^{-1}	kgPO$_4$eq	0.5743	0.6408	0.6077	0.5989	0.6592	0.5938	0.3644	0.6660	0.5886
AP ha^{-1}	kgSO$_2$eq	2.653	3.024	2.840	2.883	2.950	2.744	2.500	3.643	2.870
		Maize					**Sorghum**			
		CON	**ORG**	**CON**	**ORG**		**CON**	**ORG**	**CON**	**ORG**
Functional Unit		**ha**	**ha**	**kg**	**kg**		**ha**	**ha**	**kg**	**kg**
GWP	kgCo$_2$eq	2859.85	291.00	0.230	0.090		2305.90	267.75	0.500	0.080
EP	kgPO$_4$eq	5.640	0.5396	0.00044	0.00017		4.2940	0.6173	0.00095	0.00019
AP	kgSO$_2$eq	4.806	3.0067	0.00036	0.00097		3.7355	2.859	0.00085	0.00088
Costs		**Maize -CON**		**Maize-ORG**		**Sorghum-CON**		**Sorghum-ORG**		**Millet-ORG**
Operations (€ ha^{-1})		1706.60		526.00		934.20		479.33		479.33
Seeds (€ ha^{-1})		214.70		249.00		108.90		151.25		110.93
Pesticides (€ ha^{-1})		113.21		0.00		56.63		0.00		0.00
Fertilizers (€ ha^{-1})		274.40		0.00		203.40		0.00		0.00
Total (€ ha^{-1})		**2308.91**		**775.00**		**1303.13**		**630.58**		**590.27**
Production (t ha^{-1})		13.1		3.13		8.51		4.15		2.81
Production (€ t^{-1})		185.00		316.67		172.00		251.67		766.67
Production (€ ha^{-1})		**2423.50**		**991.18**		**1463.72**		**1044.43**		**2154.34**
Revenue (€ ha^{-1})		**114.60**		**216.18**		**160.59**		**413.85**		**1564.08**

The average GWP, EP and AP for organic (ORG) maize and sorghum are compared to conventional (CON) maize and sorghum on both a land-based and product-based (kg) approach. The Life cycle costs (LCC) are provided for environmental input categories together with production gains for ORG-cultivated millet, sorghum and maize and CON-cultivated sorghum and maize, respectively

Given that both production costs, as well as land impacts features, are worth of consideration when comparing conventional and organic systems, the present results were expressed per unit of product (kg) and per unit of land (ha), respectively. Detrimental GWP, EP and AP land impacts were significantly higher under conventional management practices compared to those of the organic system for both maize and sorghum (Table 6). In the present study, when the environmental impacts were expressed on a product basis, only the AP was higher under organic management practices (Table 6).

To better comprehend the input contribution of GWP, EP and AP, the latter outputs were categorized according to their respective inputs for organically-cultivated maize, sorghum and millet and compared to conventionally-cultivated sorghum and maize (Fig. 4).

The GWP ha^{-1} for organic millet, sorghum and maize was comparable and primarily derived from field operations (sowing, weeding and harvesting), with seeds (seed drying) representing a minor contribution (Fig. 4a). The GWP ha^{-1} of field operations for conventional maize and sorghum were slightly higher than that for the organic crops and reflected field operations pertaining to fertilizer and pesticide applications, absent under organic management. Fertilizer outputs represented by far the predominant input source of GWP ha^{-1} in the conventional system with pesticides providing a minimal contribution (Fig. 4a). Using the Agrifootprint commercial database (secondary background data), we calculated the GWP ha^{-1} of conventional maize production in Italy. The GWP ha^{-1} (4900 kg CO2-eq) exceeded that of the conventional farms in the present study but was similarly predominantly derived from fertilizers followed by field operations. Likewise, using Agrifootprint (secondary background data), we showed that the GWP ha^{-1} (similarly derived by fertilizer and field operations) of conventional sorghum in the USA was similar to that of the present study, Overall, the GWP ha^{-1} was 10-fold higher for conventional maize compared to organic maize and 6.5-fold higher in conventional sorghum compared to organic sorghum. Considering the high yields of conventional maize, the GWP kg^{-1} was two-fold higher compared to organic maize, with only fertilizer (and pesticides) outputs contributing to the difference (Fig. 4b), thereby corroborating previous research comparing conventional and organic maize (Moudry et al., 2018). The higher GWP kg^{-1} for conventional sorghum was attributable to the lower yield compared to conventional maize, with the fertilizer component similarly contributing to the 5-fold difference between conventional and organic sorghum (Fig. 4b).

Fertilizer is responsible for almost the entire impact within the category EP, mainly as a result of the emissions of the eutrophying N and P components (Meier et al., 2015). Since there was no fertilizer component for the organic crops, the EP ha^{-1} and EP kg^{-1} outputs (Fig. 4c-d) largely reflected the trends of the GWP ha^{-1} and GWP kg^{-1} for both the conventional and organic crops (Fig. 4a-b)

The land impact AP ha^{-1}, was predominantly reflected by field operations for both the organic and conventional crops (Fig. 4e). The pesticide category was also a contributory source of AP in the conventionally-cultivated maize and sorghum (Fig. 4e). The AP impact reflected by field operations scored higher under organic management under a product-based approach (Fig. 4f) compared to the conventional crops as mentioned previously.

The LCC was incorporated for the crops under investigation (Table 6). Field operations represented the highest environmental impact cost category for both the conventional and organic farms. Conventional maize incurred double the cost of conventional sorghum, which in turn was higher than the costs incurred for the organic crops (Table 6). In terms of costs gained, organic proso millet was shown to outperform both sorghum and maize for production quantity, surface area and revenue, respectively (Table 6).

4. Discussion

Given that proso millet was shown to be a promising alternative summer food crop to maize despite adverse meteorological trends over a three-year period (Ventura et al., 2022), the present study extended the performance comparisons between organic proso millet with sorghum as alternatives to maize under sustainable management practices. The potential of employing millet and sorghum as alternative food crops cannot be based solely on performances but also on sustainability. For this reason, environmental impacts were assessed comparing soil properties, as well as arthropod abundance and diversity between the conventional management system and the organic ones. Moreover, environmental impacts (air and water), and associated costs, were determined from an LCA and LCC on the organically cultivated crops and compared to conventionally-cultivated maize and sorghum in the geographical area of central-north Italy.

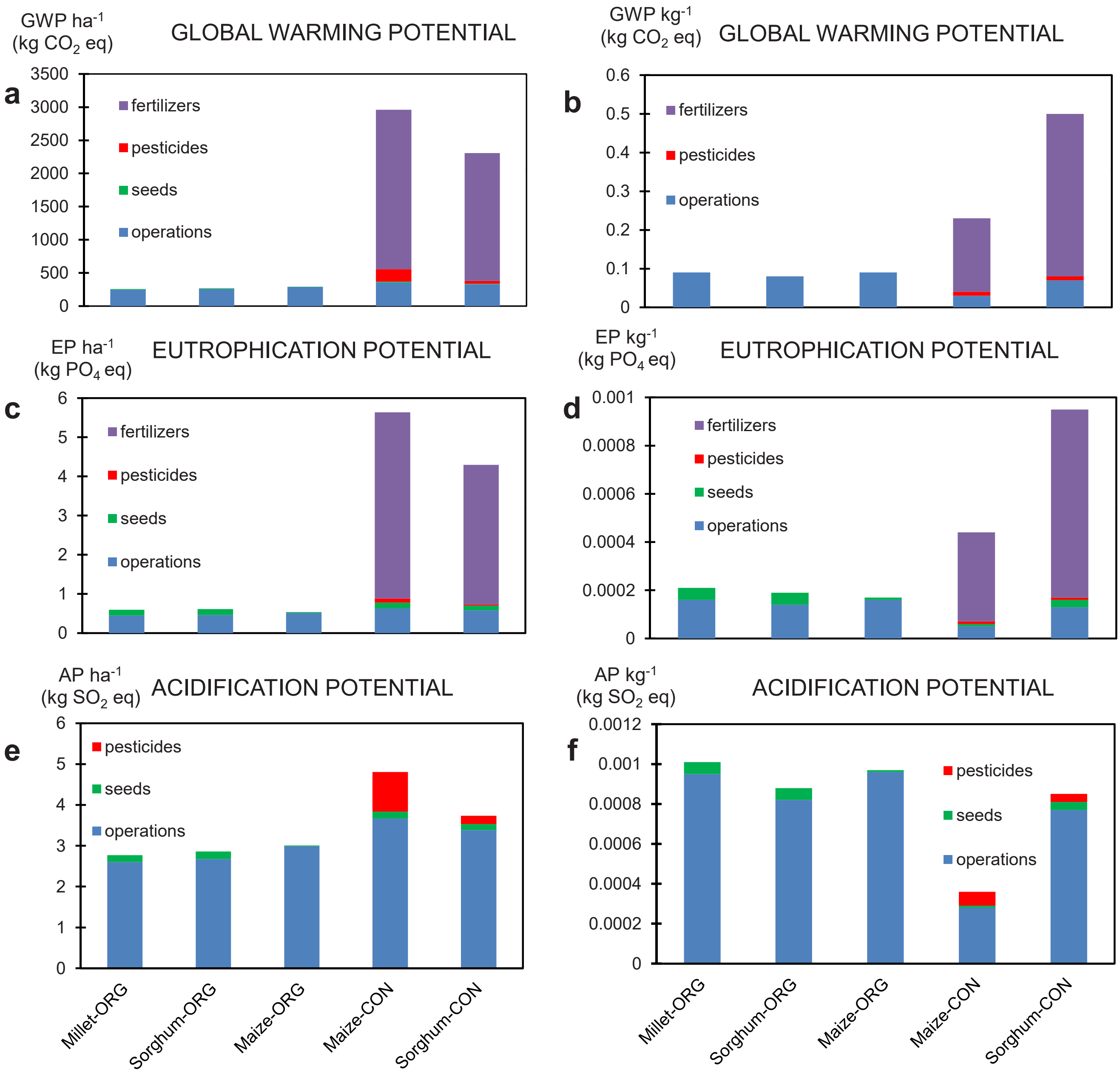

Fig. 4. Contribution of input categories (fertilizers, pesticides, seeds and field operations) on global warming potential (a-b), eutrophication potential (c-d) and acidification potential (e-f) outputs expressed on a land-based approach in ha (a, c, e) and on product-based approach in kg (b, d, f) for organically-(ORG)-cultivated millet, sorghum and maize and conventionally-(CON)-cultivated sorghum and maize, respectively.

4.1. Agronomic performance of organically cultivated proso millet, sorghum and maize

Although all three crops were cultivated under the same sustainable practices, the higher yield instability of maize (Table 4) was likely a reflection of its well-documented higher water requirement (Das et al., 2019). Despite no significant difference between sorghum, maize and proso millet yields, in terms of yield stability, sorghum did not perform as well as millet, as confirmed by the different standard error values (Table 4).

In 2021 mean and max temperatures were higher than 2020 and precipitations were overall lower. However, the few rainfalls occurred shortly after sowing, late April, and during flowering (BBCH 65), on July 13th and 16th, likely facilitated sorghum's germination and kernels formation, which were a lot more problematic in 2020. Grain per panicle and number of panicles per unit area data (Table 4) confirm the adaptation potential of millet and sorghum towards difficult climatic conditions, especially when drought occurs, and show maize's inadequacy in rainfed and organic production system.

Cultivating crops with high WUE and increased productivity is the focus of many drought-resistant crop studies (Das et al., 2019). Sustainable crop practices effective at increasing WUE, including crop rotations, crop diversification and reduced tillage (Hatfield and Dold, 2019), were implemented in the organic field trial. Given that the drier conditions in 2020–2021 did not impacted on millet's yield, it is likely that the sustainable management practices had a positive effect on the WUE of this crop and the average WUE value was comparable to previously reported values under both irrigated and water-stressed conditions (Seghatoleslami et al., 2008). Notwithstanding the sustainable crop practices, maize was shown to be lacking the drought escape, drought avoidance and drought tolerance mechanisms intrinsic to proso millet (Das et al., 2019) as well as sorghum (Verma et al., 2018).

From the disease ratings presented (Table 4), there was negligible pathogen incidence/severity to millet and sorghum, corroborating a greater disease tolerance in regions prone to adverse climatic conditions compared to maize (Bvenura and Kambizi, 2022; Das et al., 2019; van Oosterom et al., 2021). Although pathogen incidence/severity could not be considered severe for maize, the pathogenic maize smut fungus *Ustilago maydis* Corda was evident, especially in 2020–2021.

The greater vegetative cover of both millet and sorghum can be considered a key-factor in controlling weed infestation compared to maize (Table 4). However, given that crop yields of both millet and sorghum could be severely affected by uncontrolled weed infestation (Mishra, 2015), the sustainable management practices adopted in the present study can also be considered effective at controlling weeds.

From the present study, proso millet was shown to be better adapted to climate variation under sustainable management without supplementary irrigation than sorghum, showing virtually no variability in yield and WUE. However, despite a more variable yield and WUE, sorghum crop showed economically satisfactory performances, highlighting also comparable efficacy in weed competition and disease tolerance to proso millet. In contrast, based on the variations in yield, WUE, weed infestation and disease incidence and severity, organic maize cultivation could not be considered economically viable under the sustainable management practices tested in this study.

4.2. Land-based impacts on the environment: soil parameters

Aside for the superior agronomic performances of sorghum and proso millet, the potential as sustainable food crops necessitate evidence of reduced negative environmental impacts on the soil, air and water. Soils have recently become part of the global carbon agenda for climate-change mitigation and adaptation (Amelung et al., 2020). The importance of soil health was coined by the latest definition of Toor et al. (2021) as "the capacity of soils to provide a sink for carbon to mitigate climate change and a reservoir for storing essential nutrients for sustained ecosystem productivity".

The organic system was more effective at storing carbon and thereby lowering CO_2 emissions into the atmosphere and presumably the different soil tillage management had a primary role in reducing direct and indirect CO_2 emissions. In fact, the present results corroborate studies showing a link between the cropland capacity to sequester carbon into soil organic matter and the implementation of management practices such as less intensive tillage operations, rotation schemes and crop diversification (Amelung et al., 2020; De Backer et al., 2009; Toor et al., 2021; van der Werf et al., 2020). Moreover, the carbon content of the organic matter as well as other constituents therein (Fig. 2a) collectively contribute to soil health by improving soil structure, water retention, and nutrient supply to crops, agricultural productivity as well as providing food sources to fauna, enhancing ecosystem services (Amelung et al., 2020). The sustainable system was effective in promoting the preservation of organic matter, necessary in connecting environmentally sustainable agriculture with climate change mitigation (Toor et al., 2021).

Macronutrient analyses indicate that the green manure alone was sufficient in maintaining the N content with minimal variation over the three-year period. In contrast, similar minimal variation in the soil N content were associated with exogenously added N, contributing to greater emissions (see Section 3.4).

Assimilable K is also dependent on soil texture and pH. Given that silt loam has a great risk of K deficiency for plants than silty clay loam (Alfaro et al., 2004), the green manure management alone was shown to be effective in maintaining K available level, similarly to the conventional system, which employed also chemical fertilizer.

4.3. Land-based impacts on the environment: arthropod abundance, activity density and diversity

Ground dwelling arthropods are important providers of ecosystem services and are influenced by agricultural practices (Gunstone et al., 2021). To date LCA methodologies assessing impacts on biodiversity and soil parameters from positive land management practices (central in organic agriculture such as diversifying species and crop rotations) for comparisons to conventional agriculture are lacking (De Backer et al., 2009; van der Werf et al., 2020).

Given the improved soil health in terms of organic matter content under sustainable management, the objective of the experiment was then to investigate whether there were cascading effects on arthropod activity and diversity under the sustainable management, compared to the conventional ones.

These results are in line with the scientific literature, in which invertebrate communities are generally reported as less abundant and diverse in conventional farming systems if compared with more diversified cropping systems, offering a variety of habitats and resources (Norris et al., 2016; Chmelíková and Wolfrum, 2019; Otieno et al., 2021) and where rational crop rotation schemes are adopted (Meyer et al., 2019). Other potential positive impacts of the organic treatment on arthropods include the absence of synthetic pesticides and fertilizers, as they are considered as a major driving factor in recent insect declines and present an increasing threat (Gunstone et al., 2021). Similarly, intensive tillage practices (e.g. ploughing) are also reported to negatively affect ground beetle and spider assemblages (Shearin et al., 2008; Mashavakure et al., 2018).

The similar composition of ground beetle community of both managements is likely a consequence of the fact that, in both cases, communities were dominated by two generalist agrobiont species, the predominantly granivorous *Harpalus rufipes* (De Geer) (2175 individuals in the organic field, 623 individuals in the conventional field) and the opportunist predator *Pterostichus melas* (Creutzer) (428 individuals in the organic field, 138 individuals in the conventional field), which are potentially important biocontrol agents of weeds (Carbonne et al., 2020) and pests (Panni and Pizzolotto, 2018), respectively. This dominance seemed to be particularly influential in the more abundant communities of the organic system, which would also explain the fact that the Shannon and Evenness indices had often lower values in this agroecosystem if compared with the conventional ones, despite the higher number of species. These generalist species are well known for their ability to successfully exploit agricultural ecosystems (Shearin et al., 2008; Corcos et al., 2021).

Simultaneous occurrence of abundant and rich arthropod communities and high soil quality were reported also in other recent research (Menta et al., 2020); arthropod bioindicators of soil quality are indeed involved in many soil processes such as organic matter decomposition and translocation, nutrient cycling, microflora activity regulation and bioturbation (Menta et al., 2020).

4.4. LCA and LCC analysis over the three-year period for organically-cultivated proso millet, sorghum and maize, and between organic and conventional sorghum and maize

In recent years, both millets and sorghum have been increasingly recommended as potential summer-crop alternatives to maize towards mitigating food insecurity induced by climate change and agricultural impacts on global warming (Saleh et al., 2013; Saxena et al., 2018; Wang et al., 2018; Das et al., 2019; Bvenura and Kambizi, 2022; Ventura et al., 2022). Moreover, interest in both millets and sorghum as alternative food crops, as opposed to feed crops, is based on the enhanced nutritional and functional quality components (compared to major cereal grains) as well as the suitability for gluten intolerant and celiac populations (Saxena et al., 2018; Das et al., 2019; Bvenura and Kambizi, 2022). Despite, the above-mentioned recommendations, to the best of our knowledge, there is no LCA information comparing grain millet and sorghum cultivation to that of maize under sustainable management. To date LCA analyses on grain millet, sorghum and maize in conventional agriculture are scarce, with existing analyses on both maize and sorghum largely focused on industrial uses (biofuel and fiber) and feedstock (Soleymani Angili et al., 2021; Dunn, 2019). Given the requisite for more extensive published work firstly on LCA for sustainable agriculture (Meier et al., 2015; van der Werf et al., 2020) and secondly, on sorghum and millet as crops, we provided environmental impacts on the air and water in the form of GWP, EP and AP for these crops over a three-year period under organic cultivation. For the first time, we also presented a primary data comparison for both the environmental (LCA) and cost (LCC) outputs between organically- and conventionally-cultivated grain maize and sorghum (*cradle-to-farm-gate* agricultural practices) under challenging climatic conditions in central-northern Italy.

Results of the comparison between conventional farms and the farms involved in the study corroborates the large consensus that organic agriculture has lower environmental impacts per unit of land than conventional agriculture (De Backer et al., 2009; Meier et al., 2015; van der Werf et al., 2020). Given the higher yields in conventional agriculture, when outputs are expressed per unit of product, EP and AP have been reported to be significantly reduced (De Backer et al., 2009; Meier et al., 2015; van der Werf et al., 2020).

Interestingly, the lower environmental impact of organic agriculture is not only often misrepresented using the product-based approach of the LCA, but also due to inaccurate modeling within LCA from organic fertilizer sources (Meier et al., 2015). Often, EP kg^{-1} is worse in organic systems, with higher values also reflected by an overly high prediction of N losses from emission models used in LCA inventories for cereal crops, specifically from manure and organic fertilizers (Meier et al., 2015). Using the commercial database (Ecoinvent) for organic maize in Switzerland, organic fertilizers were shown to be the predominant source of EP. However, this aspect was not an issue in the present study as manure and organic fertilizers were not used to supplement the green manure rotations, which yielded no emissions. Instead, sewage and organic fertilizers were used to supplement the synthetic fertilizer sources in the conventional fields under study, and likely contributed to the higher emission impact of the fertilizer category.

Although rainfed organic maize cultivation demonstrated a lower environmental and costing impact, and potentially a greater gain than conventional maize, as mentioned previously the agronomic performance was inferior and cannot be considered viable. Of great potential as environmentally sustainable alternatives to conventional maize are organic sorghum, and more specifically organic millet from a potential cost gain and yield stability under adverse conditions. Given the enhanced nutritional and functional quality components (compared to major cereal grains) as well as the suitability for gluten intolerant and celiac populations (Saxena et al., 2018; Das et al., 2019; Bvenura and Kambizi, 2022), more research and development incentives on millet and sorghum are warranting. This would necessitate improving productivity, thereby rendering these crops more competitive to stimulate commercial demand. Simultaneously, raising productivity would also necessitate on linking farmers with markets, because only markets can give farmers the incentive to adopt improved varieties and invest in improved crop management (Orr et al., 2020). Such incentives have been introduced for millet and sorghum in Africa, which has contributed to increased productivity (Orr et al., 2020). Moreover, similar key actions to those recommended in India (Kane-Potaka et al., 2021) are requisites towards increasing cultivation under climate change in the Mediterranean Basin. The three key actions towards promoting millet consumption in India included: developing products aimed at satisfying the taste, providing knowledge on nutritional and health facts on millets, and improving accessibility of millets in urban markets (Kane-Potaka et al., 2021).

5. Conclusions

We further highlight the potential of sorghum and more specifically, organic millet cultivation as rainfed summer-crop, climate-change alternatives to maize in Italy. Under rainfed, organic management over three years, proso millet yielded consistently with stable a WUE, compared to organic sorghum and maize. Organic maize was not considered a viable alternative based on the lowest performance for yield stability, WUE, disease tolerance and weed competitive potential. The improved agronomic performance of millet and sorghum as potential food crops under sustainable management was also shown to simultaneously reduce environmental impacts on the soil, air and water. Enhanced carbon sequestration and preservation of organic matter content, increased activity density of important biological control agents (ground beetles and spiders), as well as higher ground beetle species richness were evident in the organic and sustainable management system, compared to the conventional ones. From the LCA, the GWP, EP and AP impacts per unit land, and the GWP and EP impacts per unit product of organic proso millet and sorghum cultivation were comparable and significantly lower than that of conventionally-cultivated sorghum and maize. From the LCC analysis, organic proso millet and sorghum also incurred the lowest environmental emission costs than conventional sorghum and maize. In terms of costs gained, proso millet was also shown to outperform both organic (and more specifically conventional) sorghum and maize for production quantity, surface area and revenue, respectively. Incentives to promote proso millet and sorghum cultivation under sustainable management in Mediterranean countries (facing unpredictable climate change) are recommended for the dual purpose of reducing agricultural impacts on environment and guaranteeing production, considering also their high potential as alternative raw materials for both food and feed sectors.

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CRediT authorship contribution statement

Antonio Fakaros: Writing – original draft, Visualization, Investigation, Data curation. **Francesca Ventura:** Writing – review & editing, Methodology, Conceptualization. **Serena Magagnoli:** Writing – review & editing, Investigation. **Antonio Masetti:** Writing – review & editing, Visualization, Supervision, Methodology, Formal analysis, Data curation. **Giovanni Dinelli:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Lorenzo Negri:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sara Bosi:** Writing – review & editing, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Francesco Lami:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **Giulia Oliveti:** Investigation, Data curation. **Giovanni Maria Poggi:** Investigation. **Laura Bertinazzi:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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