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Received: 20 February 2024 | Accepted: 24 January 2025

DOI: 10.1002/agj2.70026

Agronomy Journal

ORIGINAL ARTICLE

Special Section: Organic Wheat Production

Long-term evaluation of organic management of durum wheat in Central Italy

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Assigned to Associate Editor Patrick Carr.

Funding information
Ministero dell'Università e della Ricerca; Progetto FISR (Fondo Integrativo Speciale per la Ricerca) SIMBIOVEG: Sistemi e metodi di agricoltura biologica per il miglioramento della qualità delle produzioni vegetali e dell'ambiente; FP7 Coordination of Research Activities; ERA-NET Core Organic II TILMAN-ORG (Reduced tillage and green manures for sustainable organic cropping systems); ERA-NET Core Organic Plus FERTILCROP (Fertility Building Management Measures in Organic Cropping Systems)

Abstract

Italy is the most important European producer of organic (ORG) durum wheat [*Triticum turgidum* spp. *durum* (Desf.) Husn.]. Growth and yield of durum wheat are affected by weather conditions and by management systems (MS). The objective of this research was to determine the long-term impact of two different MS (ORG and conventional [CON]) and their interactions with weather conditions on durum wheat yields. The study was part of a long-term experiment in Pisa, Italy, comparing crop performance in a 5-year rainfed rotation (i.e., sugar beet [*Beta vulgaris* L. var. *saccharifera*] or maize [*Zea mays* L.] followed by common wheat [*T. aestivum* L. subsp. *aestivum* emend. Thell.], sunflower [*Helianthus annuus* L.], faba bean [*Vicia faba* L. var. *minor*], and durum wheat) over 15 years under ORG and CON MS. Durum wheat yields were 37% lower under ORG compared to CON on average, though similar yields were produced across the two systems during one of the 5-year cycles. There was a significant interaction between MS and climatic conditions for yield and yield components. A lower number of spikes per m^2 was observed in ORG wheat compared to CON, thus spotlighting on likely different soil N availability in the two MS at the double ridge stage. ORG management resulted in weed biomass increases over time, with 400% higher weed biomass under ORG by the end of the research period. The high interannual variability across both MS confirms that multi-year studies are needed to demonstrate the relative productivity of ORG versus CON MS.

1 | INTRODUCTION

Global food security for a growing population requires an increase in food production from the arable land base while maintaining environmental sustainability. Agroecological intensification is defined as "a management approach that integrates ecological principles and biodiversity management

Abbreviations: CON, conventional; GY, grain yield; HI, harvest index; LTE, long-term field experiment; MASCOT, Mediterranean Arable Systems Comparison Trial; MS, management system(s); MTE, mid-term field experiment; ORG, organic; TKW, 1000-kernel weight.

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into farming systems with the aim of increasing farm productivity, reducing dependency on external inputs, and sustaining or enhancing ecosystem services" (Garbach et al., 2016). It is also the basis for organic (ORG) agriculture, defined by the International Federation of Organic Agriculture Movements (IFOAM) as a production system that sustains the health of soils, ecosystems, and people (IFOAM, 2019). ORG agriculture relies on ecological processes, biodiversity, and natural cycles adapted to local conditions, rather than the use of synthetic inputs, which can have adverse effects, particularly when not used judiciously. ORG agriculture aims primarily to "attain ecological balance through the design of farming systems, establishment of wildlife habitats, and maintenance of genetic and agricultural diversity" (IFOAM, 2019).

To achieve these goals, in the frame of a holistic management of the farming system, a combination of well-described, environmentally friendly management practices must be employed in place of synthetic inputs (Rigby & Cáceres, 2001). For example, the United States Department of Agriculture (USDA) outlines "a system which avoids and largely excludes the use of artificial inputs" (e.g., fertilizers, pesticides, hormones, feed additives, etc.), while the *Codex Alimentarius guidelines* (WHO/FAO, 2001) and the *IFOAM basic standards* (IFOAM, 2019) prohibit the use of synthetic inputs such as fertilizers, pesticides and herbicides, veterinary drugs, and genetically modified seeds, while promoting practices that maintain long-term soil fertility and agrobiodiversity. The intent of these and other standards is to develop local and regional ORG food production and distribution systems, which are more compatible with natural cycles and maintain soil and water quality as well as biodiversity. ORG agriculture thus balances environmental, social, and economic considerations while benefiting the environment, farmer incomes, and fair relationships for all involved (Barberi, 2002).

While previous research has demonstrated the positive impact of ORG farming on soil and plant biodiversity (e.g., Barberi, 2002; Tuck et al., 2014), yield gaps in ORG compared to conventional (CON) production have been reported (David et al., 2005; Knapp & van der Heijden, 2018; Seufert et al., 2012; Smith et al., 2007), slowing the wholehearted acceptance of ORG. For example, ORG wheat yields are typically 20%–40% less than CON (David et al., 2005; De La Cruz et al., 2023; Keatinge et al., 2000), with lower yield under ORG related to a lack of weed suppression, especially perennial species, and with soil nutrient deficiencies, particularly plant-available N (Askegaard et al., 2011). From farmers' perspective, higher prices and existing premiums paid for ORG grain partially offset these lower yields (Di Cristofaro et al., 2024; Iocola et al., 2021; Mayer et al., 2015). However, a significant decrease or elimination of the reduction in grain yields (GYs) for organically grown cereal crops is imperative, as these crops play a central role in the diet of a growing global population (Lal, 2016). A possible factor contributing to the yield depression in ORG wheat and other cereals is that most of the cultivars used in modern agriculture were developed under high agrichemical input and not ORG management (Mefleh et al., 2018); as a result, seedstock is not developed to flourish under the unique selection pressures presented by ORG management system (MS) (Murphy et al., 2007, 2008). However, research strongly suggests that the incorporation of cereals into ORG crop rotations can aid in weed and disease control through crop diversification (e.g., Adeux et al., 2019; Barberi, 2002), indicating that the performance of cereal cultivars grown organically might improve if development and selection occur under ORG conditions.

Core ideas

- Grain yields were equal in organic (ORG) and conventional management only in 5 of 15 years.
- On average, durum wheat yields under ORG management were 37% less than conventional management.
- Likely main drivers of lower ORG yields were weeds and nutrient deficiencies.
- Weed biomass was greater under ORG management.
- Lower spike number in ORG was likely because of early nitrogen shortage.

Durum wheat [*Triticum turgidum* subsp. *durum* (Desf.) Husn] ranks 10th among the most cultivated crops in the world, with production concentrated in Mediterranean countries, which are not only the largest importers but also the largest consumers of durum wheat products (flour, pasta, and semolina) (Elias, 1995). In Italy, the amount of land dedicated to ORG durum wheat production has increased steadily in recent years, making the country the leading producer among European Union (EU) nations, with 1.65 million ha cultivated in 2022 (Sinab, 2024). Durum wheat grown organically leaves a smaller environmental footprint than when grown conventionally. Bux et al. (2022) found that ORG durum wheat production reduced diesel use by 15%, with a consequent reduction in CO_2 emissions. Di Cristofaro et al. (2024) utilized life cycle analysis to determine that ORG systems had 56% lower impacts on global warming, adverse effects on human health, and stratospheric ozone depletion than CON farming. However, widespread adoption still lags, related to lower ORG MS yields and linked economic consequences; for example, durum wheat generated higher income under CON than ORG management in a study by Bux et al. (2022).

The Mediterranean basin is characterized by erratic precipitation in both amount and frequency. Irregular rainfall interacts with MS, edaphic properties, and biotic stressors to directly impact durum wheat performance (Beres et al.,

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2020; Lopez-Bellido et al., 2006; Pampana & Mariotti, 2021). These interactions can be even more pronounced under ORG management because of ORG's almost-exclusive reliance on natural processes for nutrient management, such as mineralization of soil ORG matter and the use of biodiversity-related ecosystem services for weed, pest, and pathogen control. Moreover, these complex, factorial interactions evolve over time (Muneret et al., 2018; Schrama et al., 2018), making comparisons between ORG and CON methods most instructive when done in a local context in mid-term (MTE, 5–10 years) and long-term field experiments (LTEs, 10+ years) (Payne, 2013).

Despite the importance of durum wheat as a crop and the knowledge that multi-year comparisons are essential for examining the effects of ORG versus CON MS, only one Italy-based manuscript has been published on the topic. Campiglia et al. (2015) found that GY averaged 15% less in the ORG MS across a 6-year MTE. However, there was considerable variability in the annual yield gap between MS, ranging from −5% to −32%. It is unknown if the differences between MS would have persisted in an LTE (De Ponti et al., 2012; Smith et al., 2007), since relative yields of the ORG MS would either increase or decrease depending on the nutrient cycling and other natural processes that evolve over time (Petersen et al., 1999; Schrama et al., 2018). The objective of the current study was to determine how durum wheat GY compared in ORG and CON MS in the Mediterranean Arable Systems Comparison Trial (MASCOT, hereafter), a LTE located in Pisa, Italy. MASCOT was established in 2001 and is one of the oldest field experiments in the Mediterranean region where ORG and CON stockless rainfed systems are being studied (Barberi & Mazzoncini, 2006; Ciaccia et al., 2020). Specifically, we wanted to determine GY and associated variability of ORG and CON rainfed durum wheat over a 15-year (2002–2016) period in a 5-year arable crop rotation. We also wanted to determine the impacts of other issues related to MS on GY, such as weeds as represented by biomass production. We hypothesized that durum wheat GY would be both lower and more variable over time in the ORG MS, and that a higher weed biomass under ORG would be statistically related to the lower GY.

2 | MATERIALS AND METHODS

2.1 | Site description

The experiment was conducted at the Center for Agri-Environmental Research "Enrico Avanzi" (CiRAA) at the University of Pisa, located in the coastal plain region of west central Italy (latitude 43.66586 N, longitude 10.3026 E, elevation 3 m above sea level), from 2001 through 2016 (15 durum wheat growing seasons) as part of the MASCOT LTE. The MASCOT was established to compare ORG and CON arable cropping systems in the Tuscany region where ORG MS have been increasingly adopted. Alfalfa (*Medicago sativa* L.) was grown 3 years before the establishment of MASCOT, including the 2-year transition period as required by the Commission Regulation (EC) No 1991/2092, in force at that time.

Soils at the experimental site are fine loamy, mixed, xeric, calcareous Typic Xerofluvents (Soil Survey Staff, 2003). Analyses of soil at the location of the experiment prior to establishing treatments in the top 30 cm indicated the following: 44 g 100 g^{-1} sand, 33 g 100 g^{-1} silt, and 23 g 100 g^{-1} clay (modified pipette method; Indorante et al., 1990); 1.6 g 100 g^{-1} ORG matter content (Walkey and Black method; Walkey & Black, 1934), pH = 8.5 (potentiometric method; ASTM, 1995); total N = 0.1 g 100 g^{-1} (Kjeldhal method; Bremner & Mulvaney, 1982), available P_2O_5 = 30.5 mg kg^{-1} (Olsen method; Olsen et al., 1954). The climate in the area is Mediterranean (Csa), according to the Köppen classification, with low temperatures in winter that increase rapidly during spring, a hot summer, and an irregular pattern of yearly rainfall distribution, generally concentrated in autumn (October–December) and spring (February–April). Long-term mean annual precipitation is 971 mm with maximum and minimum air temperatures of 20.2°C and 9.5°C.

2.2 | Experimental layout—The MASCOT long-term experiment

A 5-year stockless arable crop rotation was established across both MS: sugar beet (*Beta vulgaris* var. *saccharifera*) followed by soft white wheat (*Triticum aestivum*), sunflower (*Helianthus annuus*), faba bean (*Vicia faba* var. *minor*), and durum wheat. In the ORG MS, red clover (*Trifolium pratense* L.) was interseeded during the tillering stage in February, by broadcasting into soft and durum wheat and then used as green manure by ploughing aboveground legume biomass into the soil 1–2 weeks before sowing the next crop (i.e., sunflower or sugar beet).

All crop phases were present each year and were rotated both in space and time across both MS. Treatments were arranged in a randomized complete block in a two (MS) by five (crop phase) factorial arrangement with treatment combinations replicated three times. Individual plot size varied slightly but averaged roughly 0.5 ha. The CON plots were separated physically from the ORG plots by natural and planted vegetation borders that were 5–8 m wide (Figure S1), with a species composition described in Rossi et al. (2019).

Durum wheat GY was determined during each of three rotation cycles (i.e., C1 = 2002 through 2006, C2 = 2007 through 2011, and C3 = 2012 through 2016). Readjustments of crop management to embed agroecological practices (e.g., relay intercropping, cover crops) were allowed to cope with

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unpredictable events or to tackle technical challenges in MASCOT (Mazzoncini et al., 2019). For example, grain maize (*Zea mays* L.) was substituted for sugar beet beginning in 2006, due to a sudden change in the EU Common Agricultural Policy and the unavailability of sugar beet seed on the market. In addition, with the beginning of the second crop rotation cycle (fall 2006), interseeded red clover was substituted with autumn sowing of a hairy vetch (*Vicia villosa* Roth) green manure, which was ploughed under 1–2 weeks before planting spring crops (maize and sunflower). The order of soft white and durum wheat was reversed in the rotation in 2007 because a greater reduction in GY and quality for soft white wheat after maize than for durum wheat was expected in this environment. Conversely, we anticipated better relative performance when growing soft white wheat after faba bean in the rotation. At the start of the third cycle (fall 2011), the autumn-sown hairy vetch monoculture was replaced with a mixture of hairy vetch and barley (*Hordeum vulgare* L.) grown as a green manure crop.

2.3 | Agronomic management of durum wheat

Local management practices that included applications of synthetic fertilizers and pesticides were used in the CON MS (Pampana et al., 2007). Management of ORG plots followed current EU regulations (1991/2092 and 2007/834) at the time of the experiment. Table 1 shows annual crop management and external inputs in CON and ORG durum wheat plots.

Generally, the seedbed was prepared by first using a moldboard plow (Mec25/Z3; Nardi) to a 25-cm depth in late summer–early autumn (September) in both CON and ORG durum wheat plots, followed by one or two passes with an S-Tine harrow (Vibromaster; Kongskilde) with 10-cm spacing vibrating tines with 10- to 15-cm soil penetration (Table 1). Wheat was sown at a 2- to 3-cm depth on the same day in both MS but on different dates across years (November–February) that is, when adequate soil moisture was available for germination and emergence. Sowing was incidentally delayed 2 days in the ORG MS in 2003 because of temporary unavailability of ORG seeds. The wheat was sown using a Gaspardo M250 planter (Gaspardo) at a density of 450 viable seeds m^{-2} (12.5-cm interrow spacing) in both MS. In 2013, heavy rainfall in autumn and winter (Table S1) prevented timely sowing of crops, and data for that year were not collected. Crop residues were harvested in CON and incorporated in ORG.

The same cultivar from a single seed lot was used to establish durum plots in both MS each year. However, Colosseo was grown in 2001 and 2002 and then replaced with Claudio from 2003 through 2016. Claudio became increasingly popular among ORG farmers over time, and untreated seed was available locally, which was not always the case for Colosseo. Still, both cultivars were among the most widely grown in Italy during our study (Careddu et al., 2024), exhibiting both high GY and yield stability (Pampana et al., 2007). The seed lots used in our study were produced in a CON MS, but ORG seed was untreated while CON seed was treated with guazatine (Panoctine L; Makhteshim Agan) fungicide.

In CON durum plots, the fertilization rates were computed targeting the crop nutrient uptake based on usual GY and nutrient concentrations. Fertilization products and timing of application were set according to local practices (Pampana & Mariotti, 2021; Pampana et al., 2007). A total of 156 kg N ha^{-1} was applied: 23% before seeding as diammonium phosphate (18-46-0) at 200 kg ha^{-1} using a Eurospan Jolly 18 centrifugal spreader (Eurospand) incorporated by S-tine harrowing, and 77% either top-dressed as liquid urea ammonium nitrate (30-0-0) at 400 kg ha^{-1} using a New Amazone UF1201 sprayer (Save) or as ammonium nitrate (27-0-0) broadcast applied at 444 kg ha^{-1} with a Eurospan Jolly 18 (Table 1).

The high unit cost of commercial ORG fertilizer coupled with its low efficiency limited fertilization in ORG durum plots to an application of 1000 kg ha^{-1} of the ORG fertilizer Nutex (desiccated and pelleted cattle manure [3-3-3], Agroqualità), as is standard practice among ORG durum farmers in Tuscany. The fertilizer was broadcast applied during the seedbed preparation and incorporated at 15-cm depth using the S-tine harrow 1–2 weeks prior to seeding. In the third crop rotation cycle (2011–2016), ORGAZOT (desiccated bloodmeal [14-0-0], AGM srl) was applied in addition as top-dressing at the rate of 200 kg ha^{-1} (i.e., 28 kg N ha^{-1}) with a Eurospand 930H spreader (Eurospand).

Herbicides were applied to control weeds in the CON MS (Table 1). In ORG plots, weeds were controlled mechanically using a 6-tine flex harrow (Hatzenbichler) at tillering (Zadoks growth stages [GS] 21–29, Zadoks et al., 1974) as needed and when soil conditions allowed. One to two fungicide treatments were applied in CON plots during the growing season when the economic threshold was reached (Table 1). Crop protection products or bioagents allowed by the European Organic Farming regulations were not applied to ORG plots in any year due to high costs and low expected efficacy, thus following the trajectory of a low-external-input approach.

2.4 | Measurements

Daily weather data (minimum and maximum air temperature, rainfall, and radiation) were obtained from an on-site automated meteorological station. The growing degree days (GDD) needed to reach crop phenological stages were

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TABLE 1 Agronomic management details when growing organic (ORG) and conventional (CON) durum wheat from 2002 through 2016 in the Mediterranean Arable Systems Comparison Trial (MASCOT) long-term experiment in Pisa, Italy.

Year	MS	Sowing date	Harvesting date	Length of crop cycle (days)	Cultivar	Fertilization	Weed control	Disease control
2002	ORG	Nov 5	Jun 24	231	Colosseo	10 Mg ha^{-1} NUTEX	Flex tine harrow	–
	CON	Nov 5	Jun 24	231	Colosseo	200 kg ha^{-1} DAP 350 kg ha^{-1} AN	Tribenuron-methyl + clodinafop-propargyl + cloquintocet-mexyl	Carbendazim + propiconazole + sulfur
2003	ORG	Feb 1	Jun 27	146	Colosseo	10 Mg ha^{-1} NUTEX	Flex tine harrow	–
	CON	Jan 30	Jun 27	148	Colosseo	200 kg ha^{-1} DAP 400 kg ha^{-1} UAN	Tribenuron-methyl + clodinafop-propargyl + cloquintocet-mexyl	Propiconazole + prochloraz
2004	ORG	Dec 20	Jul 14	207	Claudio	10 Mg ha^{-1} NUTEX	Flex tine harrow	–
	CON	Dec 20	Jul 14	207	Claudio	200 kg ha^{-1} DAP 400 kg ha^{-1} UAN	Metsulfuron-methyl + clodinafop-propargyl + cloquintocet-mexyl	–
2005	ORG	Nov 18	Jul 6	230	Claudio	10 Mg ha^{-1} NUTEX	Flex tine harrow	–
	CON	Nov 18	Jul 6	230	Claudio	200 kg ha^{-1} DAP 350 kg ha^{-1} AN	Ralcoxydim + fluroxipir + clopiralid	–
2006	ORG	Nov 24	Jul 11	229	Claudio	10 Mg ha^{-1} NUTEX	Flex tine harrow	–
	CON	Nov 24	Jul 11	229	Claudio	200 kg ha^{-1} DAP 400 kg ha^{-1} UAN	Tribenuron-methyl + clodinafop-propargyl + cloquintocet-mexyl	–
2007	ORG	Dec 29	Jun 25	178	Claudio	10 Mg ha^{-1} NUTEX	Flex tine harrow	–
	CON	Dec 29	Jun 25	178	Claudio	200 kg ha^{-1} DAP 400 kg ha^{-1} UAN	Mefenpyr-diethyl + iodosulfuron-methyl-sodium	–
2008	ORG	Nov 30	Jun 25	208	Claudio	10 Mg ha^{-1} NUTEX	Flex tine harrow	–
	CON	Nov 30	Jun 25	208	Claudio	200 kg ha^{-1} DAP 400 kg ha^{-1} UAN	Florasulam + clodinafop-propargyl + cloquintocet-mexyl + ethoxylated sorbitan monooleate	Propiconazole + prochloraz
2009	ORG	Feb 26	Jun 30	124	Claudio	10 Mg ha^{-1} NUTEX	Flex tine harrow	–
	CON	Feb 26	Jun 30	124	Claudio	200 kg ha^{-1} DAP 350 kg ha^{-1} AN	Mefenpyr-diethyl + iodosulfuron-methyl-sodium	Flutriafole + prochloraz
2010	ORG	Nov 26	Jun 28	214	Claudio	10 Mg ha^{-1} NUTEX	Flex tine harrow	–
	CON	Nov 26	Jun 28	214	Claudio	200 kg ha^{-1} DAP 350 kg ha^{-1} AN	Mefenpyr-diethyl + iodosulfuron-methyl-sodium	–
2011	ORG	Feb 10	Jun 30	140	Claudio	10 Mg ha^{-1} NUTEX	Flex tine harrow	–
	CON	Feb 10	Jun 30	140	Claudio	200 kg ha^{-1} DAP 175 kg ha^{-1} AN	Mefenpyr-diethyl + iodosulfuron-methyl-sodium	–

(Continues)

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TABLE 1 (Continued)

Year	MS	Sowing date	Harvesting date	Length of crop cycle (days)	Cultivar	Fertilization	Weed control	Disease control
2012	ORG	Nov 3	Jun 26	236	Claudio	10 Mg ha^{-1} NUTEX 200 kg ha^{-1} ORGAZOT		–
	CON	Nov 3	Jun 26	236	Claudio	200 kg ha^{-1} DAP 350 kg ha^{-1} AN	Mesosulfuron-methyl + mefenpir-diethyl + MCPA (2-methyl-4-chlorophenoxyacetic acid)	–
2014	ORG	Dec 10	Jun 19	191	Claudio	10 Mg ha^{-1} NUTEX 200 kg ha^{-1} ORGAZOT		–
	CON	Dec 10	Jun 19	191	Claudio	200 kg ha^{-1} DAP 350 kg ha^{-1} AN	Mesosulfuron-methyl + mefenpir-diethyl + MCPA	–
2015	ORG	Jan 13	Jun 23	161	Claudio	10 Mg ha^{-1} NUTEX	Flex tine harrow	–
	CON	Jan 13	Jun 23	161	Claudio	200 kg ha^{-1} DAP 350 kg ha^{-1} AN	Mesosulfuron-methyl + mefenpir-diethyl + MCPA	–
2016	ORG	Nov 11	Jun 24	226	Claudio	10 Mg ha^{-1} NUTEX 200 kg ha^{-1} ORGAZOT		–
	CON	Nov 11	Jun 24	226	Claudio	200 kg ha^{-1} DAP 350 kg ha^{-1} AN	Mesosulfuron-methyl + mefenpir-diethyl + MCPA	–

Abbreviations: AN, ammonium nitrate; DAP, diammonium phosphate; MS, management system; UAN, urea ammonium nitrate.

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computed using the following equation:

$$\mathrm{GDD} = \left(T_{\max} + T_{\min}\right)/2 - T_{\mathrm{base}} \quad (1)$$

where $T_{\max} + T_{\min}$ are the maximum and minimum temperatures (°C), respectively, and T_{base} is the temperature below which no significant crop development occurs. We assumed a T_{base} of 5°C from sowing to early stem elongation (Zadoks GS 0–30) and 10°C from stem elongation to physiological maturity (Zadoks GS 30–89).

At physiological maturity, that is, Zadoks GS 92, plants were manually cut with pruning shears at the soil surface within four 1 m^2 quadrants (including eight wheat rows and eight inter-rows) and separated into crop and weeds. Dry weed biomass was determined by oven-drying samples at 100°C to constant weight. Durum wheat plants were separated into culms and spikes (ears). The spikes were counted to determine the number per m^{-2}, and then oven-dried at 65°C until constant weight. They were then weighed and threshed using a self-fabricated thresher and separated into grain and chaff. Dry weight was determined separately for straw, chaff, and grain. Dry GY and straw biomass were reported in Mg dry matter (DM) ha^{-1}. Note that 1000-kernel weight (TKW) was determined on three, 100-kernel subsamples. Harvest index (HI) was calculated as the ratio between grain dry weight and aboveground total biomass dry weight, as a percentage. Grain was harvested in the remaining portion of each plot using a harvester (Claas Lexion 760). Wheat straw was removed from plots using a round baler (New Holland 658) in the CON MS and left in plots in the ORG MS.

2.5 | Statistical analysis

A uniform correlation structure was assumed for the repeated observations from each plot since observations of the same plots with the same preceding crop occurred every 5 years (Payne, 2013). Data were analyzed to evaluate not only Year (Y) (i.e., a combination of both spatial and temporal sources of inter-subject variability) but also the effect of the three rotation cycles: first from 2002 through 2006, second from 2007 through 2011, and third from 2012 through 2016. All statistical analyses were done using R software (R Core Team, 2021), version 4.2.3 "Shortstop Beagle." Different linear models were selected to assess the effect of MS and time (i.e., Year [Y] or crop rotation cycle [C]) on the measured variables, according to the goodness of fit.

When testing the time as year (Y), the fixed effects included in the model were block, Y, MS, and the interaction Y × MS, while plots and blocks were considered random effects (with plots nested within blocks). For GY, TKW, and HI, a general linear mixed-effects model was fitted, using the lmer() function from the "lme4" package (Bates et al., 2015). For straw biomass, a generalized linear mixed-effects model using a Gamma distribution (with identity as link function) was fitted using the glmer() function from the "lme4" package. For the number of ears, a negative binomial regression model was applied (with log as link function) using the glm.nb() function from the "MASS" package (Venables & Ripley, 2002). For weed biomass, a generalized linear mixed-effects model was fitted using the glmmTMB() function from the "glmmTMB" package (Brooks et al., 2017) with a lognormal distribution (with log as link function).

When testing the time as crop rotation cycle (C), the fixed effects included in the model were block, C, MS, and the interaction C × MS, while plots and blocks were considered random effects (with plots nested within blocks). For GY and straw biomass, a generalized linear mixed-effects model using a Gamma distribution (with identity as link function) was fitted using the glmer() function from the "lme4" package. For TKW and HI, a general linear mixed-effects model was fitted, using the lmer() function from the "lme4" package. For the number of ears, a negative binomial regression model (with log as link function) was applied using the glm.nb() function from the "MASS" package. For weed biomass, a generalized linear mixed-effects model was fitted using the glmmTMB() function from the "glmmTMB" package, with a zero-inflated Gamma distribution (with log as link function).

Tukey's honestly significant difference post hoc test at $p < 0.05$ was carried out for pairwise multiple comparisons using the "emmeans" R package (Lenth et al., 2018) with the emmeans() function. The Levene test was used to check the homogeneity of variance and the Shapiro–Wilk test to check the normality of residuals. Data transformation was not necessary.

3 | RESULTS

3.1 | Weather

Yearly precipitation ranged from 51% to 120% of the total amount received on average over the 15-year study, with 2012 being the driest (399 mm) and 2013 the wettest (1251 mm) years (Table S1). Total precipitation during the growing season (sowing to harvest dates, Table 1) was variable, ranging from 150 mm in 2003 to 632 mm in 2010 (Table 2), depending also on a different length of the growing season due to sowing dates. Overall, the third rotation cycle received greater amounts of precipitation (462 mm) than the first and second rotation cycles. Precipitation received early, from sowing through stem elongation (Zadoks GS 30), averaged 42%–67% less during the second than first and third rotation cycles. Conversely, late-season precipitation (stem elongation to physiological maturity, Zadoks GS 30–89) was 30%–22%

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TABLE 2 Cumulative rainfall and growing degree days (GDD) in a 5-year rotation during the durum wheat crop phase, from sowing to stem elongation (early) and from stem elongation to maturity (late), for three rotation cycles (C1, C2, and C3) in Pisa, Italy.

	Rainfall			GDD		
Year	Total (mm)	Early (mm)	Late (mm)	Total (˚C)	Early (˚C)	Late (˚C)
2002	420	238	182	976	347	629
2003	150	12	139	798	18	780
2004	520	249	271	939	198	741
2005	433	265	168	1004	244	760
2006	495	378	117	994	162	833
avg C1	403	228	175	942	194	749
2007	354	126	228	974	260	714
2008	511	272	239	874	261	613
2009	288	0	288	772	10	762
2010	632	313	319	862	247	615
2011	253	88	165	816	57	759
avg C2	408	160	248	860	167	693
2012	399	180	219	1034	418	616
2013	–	–	–	–	–	–
2014	539	397	142	923	361	562
2015	309	156	153	781	148	633
2016	604	340	264	1138	515	624
avg C3	462	268	194	969	361	609
15-year avg	422	215	207	920	232	689

Note: Data of 2013 growing season are not presented because the crop was not sown because of harsh weather.

greater during the second than first and third rotation cycles. Moreover, the second rotation cycle was cooler than the other two cycles, with average accumulated GDDs in the growing period totaling 860 for the former and 942–969 for the first and third cycles. Accumulated GDDs were low early in the growing season (167 GDDs) for the second rotation cycle, averaging 27 and 194 fewer GDDs than the first and third rotation cycles.

3.2 | Durum wheat response to management system

An interaction was detected between year and MS for all durum wheat production variables (Table 3). For GY, differences were not detected between MS in 5 years (2002, 2008, 2011, 2012, and 2014), but were 1.0–4.5 Mg ha^{-1} greater in the CON MS in other years (Figure 1). Differences between the two MS were greatest in 2015 when GY was 77% lower across ORG (1.31 Mg ha^{-1}) compared to CON (5.79 Mg ha^{-1}) MS plots. Overall, GY was nearly 50% less when durum wheat was grown in ORG MS (2.51 Mg ha^{-1}) than the CON MS (4.12 Mg ha^{-1}) plots across the 15-year experiment. GY also was more variable in ORG MS (coefficient of variation [CV] = 55%) than in CON MS (CV = 37%) plots across the 15-yr experiment (Table S3). The CV increased for both MS as the study progressed, from 24% to 38% in CON and from 34% to 51% in ORG plots from the first to the third crop phases.

Wheat straw biomass was similar between MS in 2002, 2012, and 2014 (Table 3), as was the case for GY (Figure 1). Conversely, differences in wheat straw biomass were not detected between MS in 2005 and 2006, while GY was 19% and 23% lower in ORG than CON plots those years. Straw biomass was lower in ORG MS plots compared to CON MS plots in other years, with the greatest differences between ORG and CON MS detected in 2010 (1.58 vs. 4.22 Mg ha^{-1}) and 2015 (1.26 vs. 4.03 Mg ha^{-1}) (Figure 1). Wheat straw biomass was more variable in ORG MS (CV = 51%) than CON MS (CV = 35%) across the 15-year experiment (Table S3), with variability increasing over time, averaging 42% during the first (2002–2006), 47% in the second (2007–2011), and 65% in the third crop phase (2012–2016) in ORG plots, and 28%, 38%, and 41% in CON MS plots.

The HI was lower for durum wheat in CON MS than ORG MS plots in 2002 (0.35 vs. 0.39) but greater in CON MS plots in both 2014 (0.45 vs. 0.40) and 2015 (0.51 vs. 0.44) (Table S2). Differences in HI were not detected between the two MS in other years. Similarly, an interaction between year and MS was detected for durum spike density. Spike density was greater in CON than ORG MS plots in all years except 2002, 2008, 2011, and 2014, as was the case for GY (Figure 1; Table

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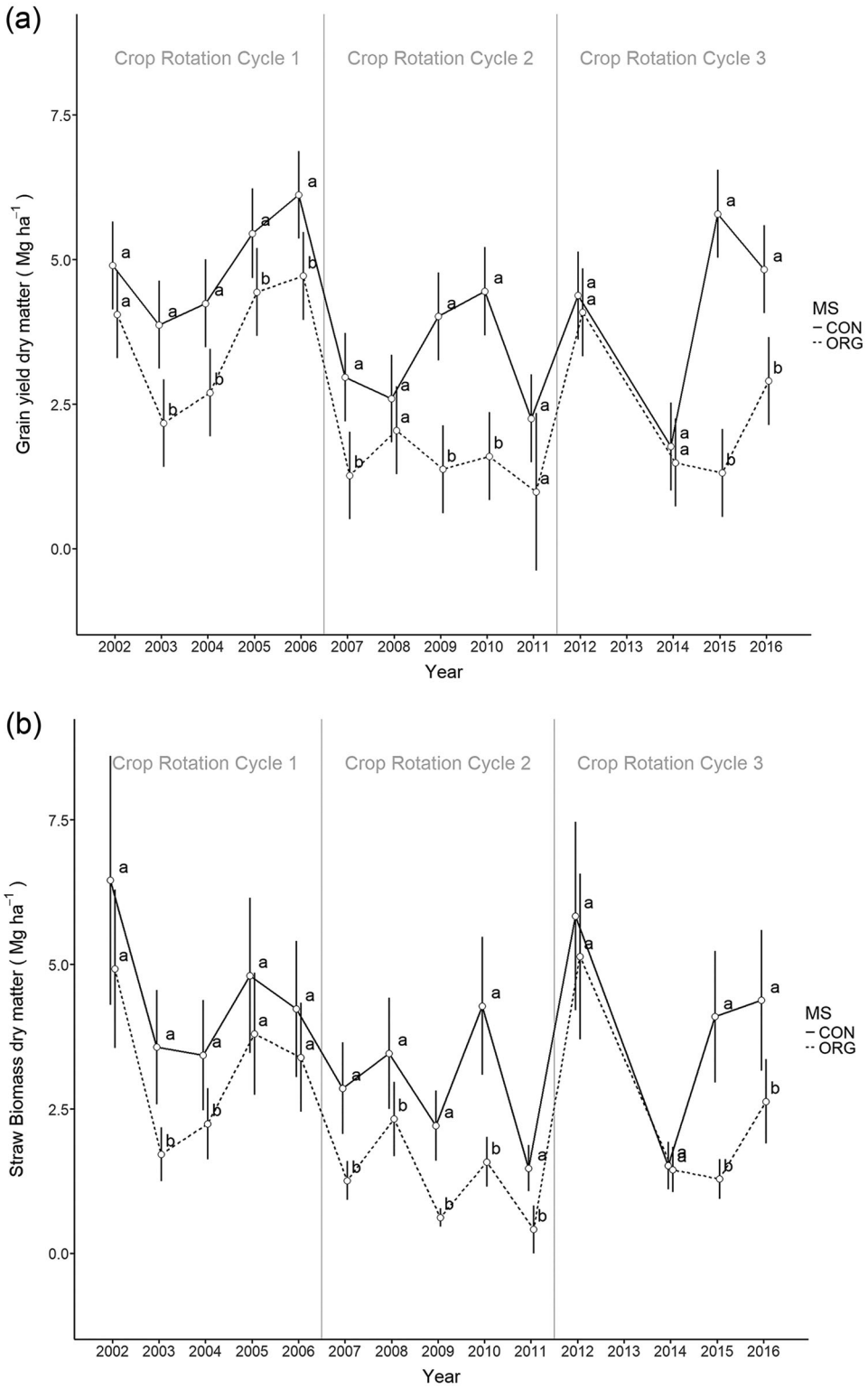


FIGURE 1 Durum wheat grain dry matter yield (a) and aboveground dry biomass production (Mg ha^{-1}) (b) under conventional (CON) and organic (ORG) management from 2002 through 2016 in a long-term study in Pisa, Italy. Within years, values with the same letter are not statistically different at $p < 0.05$. Vertical solid lines represent the confidence interval. MS, management system.

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TABLE 3 *p*-values and residual variance associated with analysis of variance (ANOVA) for grain yield (GY), straw biomass (SB), harvest index (HI), 1000-kernel weight (TKW), number of spikes per square meter (NS), and weed biomass (WB) with sources of variation and degrees of freedom for the main effects and the interactions of year and management system.

		p value > *F*					
Source of variation	***df***	**GY**	**SB**	**HI**	**TKW**	**NS**	**WB**
Block	2	0.001	<0.001	0.010	0.030	0.041	0.076
Y	13	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
MS	1	0.069	<0.001	0.020	0.287	0.140	<0.001
Y × MS	13	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Residual variance		0.196	0.029	0.000	2.313	1.029	0.056

Abbreviations: MS, management system; Y, year.

TABLE 4 *p*-values and residual variance associated with analysis of variance (ANOVA) for grain yield (GY), straw biomass (SB), harvest index (HI), 1000-kernel weight (TKW), number of spikes per square meter (NS), and weed biomass (WB) with sources of variation and degrees of freedom for the main effects and the interactions of crop rotation cycle and management system.

		p value > *F*					
Source of variation	***df***	**GY**	**SB**	**HI**	**TKW**	**NS**	**WB**
Block	2	0.269	0.700	0.649	0.798	0.696	0.470
C	2	<0.001	<0.001	0.225	0.003	0.118	0.077
MS	1	<0.001	<0.001	0.742	0.923	<0.001	<0.001
C × MS	2	0.732	0.775	0.666	0.056	0.541	0.007
Residual variance		0.108	0.170	0.003	11.209	1.020	0.209

Abbreviations: C, crop rotation cycle; MS, management system.

S2). In 2012, more spikes occurred in CON than ORG MS plots (496 vs. 398 spikes m^{-2}), while GY was similar between MS that year, averaging 4.2 Mg ha^{-1}. Over the 15-year study, spike density was 37% greater in the CON MS (384 spikes m^{-2}) compared to the ORG MS (280 spikes m^{-2}) (Table 4; Table S2). An interaction was detected between year and MS for TKW (Table 3). Kernels produced in CON MS plots had a heavier TKW than those produced in ORG MS plots in 2003, 2012, 2014, 2015, and 2016 (Table S2). No differences were detected in TKW between MS in other years.

3.3 | Management system impacts on weed biomass

Weed biomass was on average fourfold higher in ORG (i.e., 0.81 Mg ha^{-1}) than in CON (0.22 Mg ha^{-1}) MS plots, but there was a year by MS interaction (Figure 2; Table 3). Differences in weed biomass were not detected between MS in four of the first 5 years of the study, with 2004 being the exception. However, weed biomass was greater in ORG than CON MS plots in the remaining years in which weed biomass was determined, except for 2008. Differences in weed biomass between MS were greatest in 2014, with roughly 3 Mg ha^{-1} produced in ORG plots compared to 0.3 Mg ha^{-1} in CON plots. Not only was there more weed biomass produced in ORG than CON MS plots during each 5-year crop rotation cycle, but there was also greater year-to-year variability in ORG than CON MS plots. Weed biomass ranged from 0.03 to 0.37 Mg ha^{-1} in CON MS plots, except in 2011 when 1.07 Mg ha^{-1} was produced. In contrast, in ORG MS plots, weed biomass ranged from 0.02 to 2.95 Mg ha^{-1}, with dramatic shifts in DM production between 2011 and 2012 (2.11 vs. 0.65 Mg ha^{-1}) and between 2014 and 2015 (2.95 vs. 0.84 Mg ha^{-1}).

4 | DISCUSSION

Increasing production and quality of food grown organically is needed to meet an increasing global demand for ORG food products by a growing population. Besides dietary shift and food waste reduction, crop yield under ORG management must be increased to reduce the need for additional cultivated land and to enhance the energy efficiency of ORG food production (Muller et al., 2017). A challenge of working with ORG MS is that some of the practices, such as reliance on green manures or ORG fertilizers to meet crop nutrition needs, have a more nuanced impact compared with the application of synthetic N fertilizers, particularly in the short term. Nevertheless, maintaining adequate soil fertility in ORG MS (e.g., by using farmyard manure as soil amendment) is essential to minimize the effects of biotic and abiotic stressors on crops

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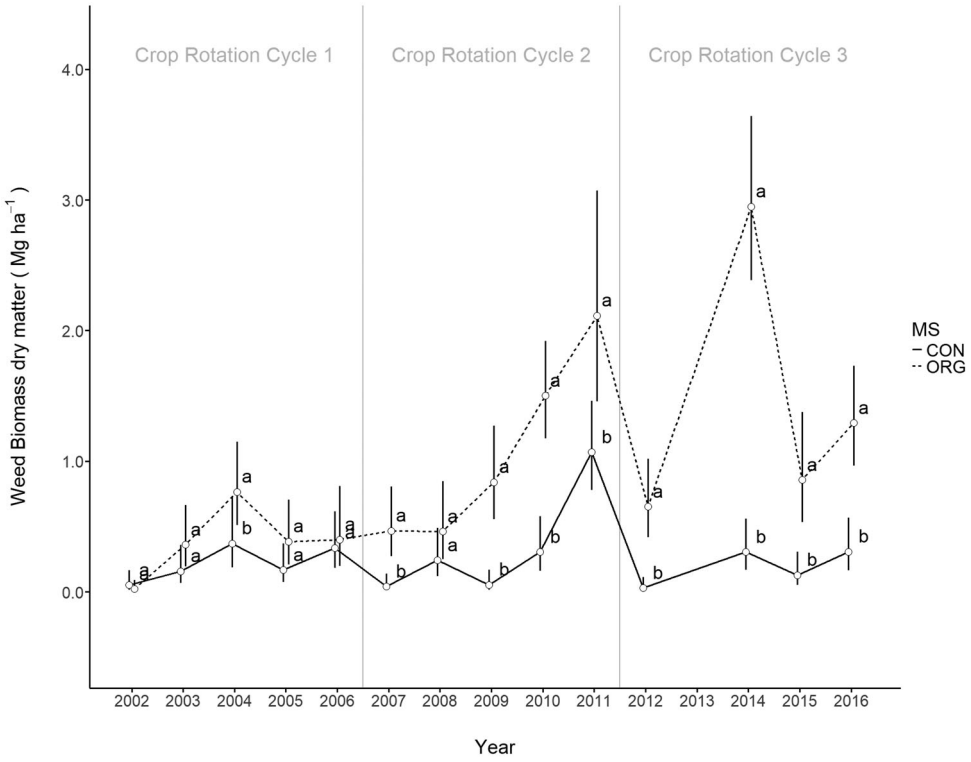


FIGURE 2 Total dry aboveground biomass (Mg ha^{-1}) of weeds at harvest of durum wheat as affected by year and management system (MS) in a long-term conventional (CON) and organic (ORG) comparison in Pisa, Italy. Within each year, values with the same letter are not statistically different for $p < 0.05$. Vertical solid lines represent the confidence interval.

that can be exacerbated by a ban on synthetic fertilizers and pesticides.

ORG farming can impact soil fertility and ORG matter dynamics over time (Aulakh et al., 2022; Gattinger et al., 2012), making long-term studies necessary to quantify the effect of ORG management on crop GY as mediated by soil fertility dynamics (Oldfield et al., 2019). In Italy and other Mediterranean environments, increasing soil ORG matter under ORG farming management can prove challenging because soils are prone to erosion, and there can be high mineralization rates of ORG C (Aguilera et al., 2013). This challenge is greatest in stockless systems with no link to animal husbandry since animal manure is not available for use as a source of ORG matter to improve soil fertility (Schulz et al., 2014). With this in mind, we used data from a long-term study (MASCOT) in Pisa, Italy, to compare the effect of stockless ORG versus CON MS on GY yield and production parameters of durum wheat, one of the most important commodity grain crops grown in the country.

On average, durum wheat GY was 37% lower in ORG compared to CON MS in our study, with significantly lower grain production in the ORG MS in 10 of the 14 years considered. Our results align with previous research indicating lower yield for crops when grown organically (David et al., 2005; De La Cruz et al., 2023; Keatinge et al., 2000). The average GY produced by ORG durum wheat in our study (2.6 Mg ha^{-1}) was in line with the observations of short-term studies conducted in Italy (Campiglia et al., 2015; Carucci et al., 2021; Di Mola et al., 2021; Fagnano et al., 2012). Similarly, the average GY of CON durum wheat in our study (4.1 Mg ha^{-1}) was representative of average GY of durum wheat in central Italy (EUROSTAT, 2024).

Our results showed that durum wheat GY varied considerably across years in both ORG and CON MS. This observation demonstrates the impact that weather has in determining the success of durum wheat production in central Italy and similar environments, regardless of MS, and in explaining the temporal variability in GY, consistent with previous research (Beres et al., 2020; Campiglia et al., 2015). Interestingly, in our study, ORG GY showed greater temporal variability with a widening gap over time compared to CON GY, in contrast to previous research suggesting that ORG MS has greater yield stability (e.g., Schrama et al., 2018). However, Campiglia et al. (2015), in a similar Mediterranean environment, observed greater GY variability in an ORG system along with a widening yield gap over time. Future research is needed to elucidate the mechanisms that explain a narrowing of the yield gap and greater yield stability for ORG compared to CON MS in some environments and management conditions but not in others.

Previous research documented increases in soil ORG C in ORG compared to CON plots at the end of the first 5-year rotation cycle (C1) of the MASCOT LTE (Mazzoncini et al.,

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2010). Hence, we hypothesized that greater amounts of plant-available N would be released because of higher amounts of soil ORG matter in ORG plots, minimizing the need for additional N to supplement natural fertility levels. However, our expectation was not supported by the results of this study. Rather, our results and those of previous research (e.g., Lopez-Bellido et al., 2006) indicate that N deficiency generally exists when growing ORG durum wheat in Mediterranean climates (Carucci et al., 2021; Rharrabti et al., 2003).

A shortage of plant-available N develops in Mediterranean climates because soil ORG matter mineralization generally peaks in autumn and spring, coincident with maximum rainfall amounts, increasing the risk of N loss through leaching or denitrification (Tosti & Guiducci, 2010). This risk is higher in years characterized by higher rainfall in fall–winter and early spring, resulting in low levels of plant-available N in soil during those times (Tosti & Guiducci, 2010). Spikelet formation (Zadoks GS 29–30) begins in early spring and is favored by sufficient soil mineral N availability (Toyota et al., 2001), with deficiencies leading to GY depression due to low number of kernels per square meter (Demotes-Mainard et al., 1999). The lack of plant-available N in CON MS can be corrected by the application of synthetic N fertilizer but presents a challenge in ORG MS due to unpredictable rates of ORG fertilizer mineralization of plant-available N release. In our study, we observed a significantly lower number of spikes per square meter in ORG plots. We suggest that ORG wheat plants have produced less tillers per plant and/or less spikes per tiller due to limited N availability from sowing to the end of tillering, whereas in the CON plots this N deficiency condition might have been overcome by the first mineral N fertilizer application (36 kg N ha^{-1} as ammonium diphosphate).

In late spring, dry conditions develop in Mediterranean climates, reducing N mineralization and water and nutrient absorption by wheat crop roots (Tosti & Guiducci, 2010). This leads to decreases in the leaf area and photosynthetic activity of wheat plants, thereby reducing the accumulation and translocation of carbohydrates to spikes and subsequently lower GY (Pampana et al., 2007). The low soil N conditions that are prevalent in ORG MS within Mediterranean environments led Murphy et al. (2007) to conclude that cultivars adapted to low N conditions are needed when growing wheat organically, especially in low rainfall environments.

Weed pressure was a key limiting factor of ORG cereal crop GY in previous research (Barberi, 2002). In our study, weed biomass at harvest time was considered as a proxy of weed pressure and increased over time in the ORG MS, as occurred in other studies (e.g., Campiglia et al., 2015). We speculate that weed composition likely diverged in the ORG MS with respect to the CON MS due to the selective effects of the synthetic herbicides applied in the latter MS, though data supporting this conjecture were not systematically collected in our study. Specific analyses on weed assemblage in ORG versus CON MS LTE are needed to better understand if and why this divergence occurs, and if this led to strong competition between the crop and the weeds based on functional traits of weed species.

In our study, direct mechanical weeding at the levels applied was insufficient for adequate weed control in the ORG MS. In part, the unpredictable and erratic rainfall made it difficult to time cultivation to maximize efficacy in weed control based on soil condition (not too wet or too dry), thus reducing the effectiveness of flex-tine harrowing (Mouazen et al., 2007). For example, April rainfall was only 24 mm in 2011, preventing effective weed control in ORG MS, because of the dry soil conditions that also reduced weed uprooting by the harrow. As a result, weeds produced about 2 Mg ha^{-1} of aboveground biomass that year, almost double the 15-year average of the ORG MS. Work is needed to develop integrated weed management strategies that can suppress weeds effectively when cultivation effectiveness is limited because of environmental conditions.

Crop rotation is one component of the most effective integrated weed management strategies (Arnhold et al., 2023; Ercoli et al., 2017). Initially, durum wheat was the last crop grown in the five crop rotation in the current study, after faba bean. However, after the first rotation cycle (2002–2006), durum wheat was moved and followed maize which was substituted for sugar beet in the second (2007–2011) and third (2012–2016) rotation cycles (please see above for the reasons). Along with this change came the replacement of red clover interseeding in durum wheat with an autumn sowing of hairy vetch after the durum wheat harvest. The placement of durum wheat after maize rather than faba bean likely resulted in low amounts of plant-available N in the soil following maize because of its high N demand, thereby reducing the growth of wheat plants and the ability to compete with weeds for growth resources. The competitiveness of the wheat crop was reduced further by the absence of interseeded clover, which was used to reduce weed pressure in other studies when growing cereal crops (Leoni et al., 2022).

Another factor related to crop rotation that may help explain the increases in weed biomass over time in our study is the residual effect of an alfalfa hay crop. Alfalfa was grown in fields before starting the present study, and many studies demonstrated that weeds were suppressed when this forage crop was grown (e.g., Burke et al., 2024). Hence, the weed seed bank likely was depleted when the LTE began, with a clean seed bank, but was replenished over time in a rotation that excluded alfalfa and other perennial forage crops. Unfortunately, the systems approach used in our study made it impossible to disentangle the specific reasons why weed biomass increased over time, particularly in the ORG MS. Our study suggests that the combined effect of stockless crop rotation and direct mechanical management may be insufficient in suppressing weeds in Mediterranean environments, under-

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scoring the need for research that identifies the combination of practices that maintain weeds at a tolerable level in stockless ORG MS (Armengot et al., 2015).

5 | CONCLUSION

Results of the MASCOT LTE highlight the potential production limitations and instability of stockless ORG cereal systems in Mediterranean environments. The lack of access to livestock manure can lead to plant nutrient deficiencies that are difficult to overcome in these environments. Future research is needed to determine how to maintain adequate soil fertility for optimum GY in these systems. Additional challenges to the sustainability of stockless ORG MS are posed by weeds and their propensity to increase over time. Wheat genotypes that are bred for low-N ORG environments and are competitive with weeds can help address these challenges and are needed, along with refinements in crop rotation design and the strategic use of tillage and other practices that can stabilize and improve ORG GY. Finally, high interannual variability indicates that multi-year studies are imperative to fully understand the comparative productivity outcomes of different ORG MS, particularly research that links specific weather trends to soil nutrient dynamics and crop growth and development. Interdisciplinary teams of scientists and farmer collaborators will be needed to direct and execute this research because of the complexities of the systems and interactions of factors that should be considered.

AUTHOR CONTRIBUTIONS

Daniele Antichi: Conceptualization; funding acquisition; investigation; methodology; validation; writing—original draft; writing—review and editing. **Silvia Pampana**: Conceptualization; writing—original draft; writing—review and editing. **Massimo Sbrana**: Conceptualization; data curation; investigation; methodology. **Lorenzo Gabriele Tramacere**: Conceptualization; investigation; writing—original draft; writing—review and editing. **Marco Mazzoncini**: Conceptualization; funding acquisition; investigation; methodology; resources. **Stefano Carlesi**: Conceptualization; funding acquisition; investigation; methodology; validation; writing—original draft; writing—review and editing. **Paolo Barberi**: Conceptualization; funding acquisition; investigation; resources; supervision.

ACKNOWLEDGMENTS

The authors would like to acknowledge the two anonymous reviewers and the editors for their valuable comments on the manuscript. The authors are also grateful to Dr. Debra Christie for her kind help in professionally revising the language of the manuscript. A special thank goes to all the technical staff of the Centre for Agri-environmental Research "Enrico Avanzi" who contributed to implement the field trial and to plant sampling and analysis.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Antichi, D., Pampana, S., Sbrana, M., Tramacere, L. G., Mazzoncini, M., Carlesi, S., & Bàrberi, P. (2025). Long-term evaluation of organic management of durum wheat in Central Italy. *Agronomy Journal*, *117*, e70026. https://doi.org/10.1002/agj2.70026

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