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RESEARCH ARTICLE

Agronomic management strategies to increase soil organic carbon in the short-term: evidence from on-farm experimentation in the Veneto region

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Abstract

Background and aims Organic fertilizers and cover crops (CC) are considered crucial strategies to pursue the objective of increasing soil organic carbon (SOC). The present research focuses on an 'on farm experimentation' to assess the combined effects of organic fertilization with different biomasses, CC and irrigation on SOC stock.

Methods A 4-year on-farm experimentation was co-developed with local farmers and a land reclamation authority in north-eastern Italy on a biennial maize-soybean rotation. We examined the effects of two organic fertilizers (compost or digestate), three CC treatments (a fixed cover crop species – *x triticosecale*; a succession of cover crop species – *Sinapis alba* and *Lolium multiflorum*; no CC) under rainfed and irrigated conditions on the SOC content and stock, and crops yields.

Results All these integrated practices – except when digestate was applied in the field in the absence of a CC under rainfed conditions – determined a significant increase of the SOC stock after 4 years, matching the goals set by the '*4 per mille*' initiative. The highest SOC increase was observed under irrigated management and compost fertilization, regardless of the presence or absence of a CC (range: 9.3–10.3 Mg ha^{-1} in the first 0–40 cm of soil). Soybean grain yields were comparable with those obtained in farms of the same rural district under business as usual, but maize grain yields were lower.

Conclusion SOC accumulation is achievable in the short term with abundant applications of organic biomass, but the strategy might lead to economic loss such as lower maize productivity.

Keywords Digestate · Compost · Irrigation · Cover crops · Maize-soybean rotation · Organic matter

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Introduction

Promoting soil organic carbon (SOC) storage, considered as a proxy for soil organic matter (SOM)

accumulation and soil health, is crucial in the path towards a more resilient agriculture able to mitigate climate change (Lal 2004). At COP21 (Paris 2015), the '4 per mille Soils for Food Security and Climate' was launched to increase global SOM by 4 per 1000 per year to compensate for anthropogenic greenhouse gas emissions (Rhodes 2016; Rumpel et al. 2020; https://4p1000.org/?lang=en). In the same perspective, the EIP-AGRI Focus Group 'Soil Organic Matter in Mediterranean regions' brought together scientists with different expertise to formulate valuable and feasible solutions to improve SOM in the Mediterranean area in order to overcome the excessively widespread condition of soils with an organic carbon (OC) content lower than 1% in southern Europe (Zdruli et al. 2004). The SOC stock was proposed as an indicator to monitor land and soil degradation. Supplementing the soil by returning the cash crop residues and cover crop (CC) biomass, together with external OC sources (digestate, manure, compost) is considered as a complementary strategy with a potential to increase SOC in many agroecosystems (Costantini et al. 2020) and has been listed among the best practices by the EIP-AGRI working group on SOM. The increase of the SOC stock can contribute to Agenda 2030 for Sustainable Development (Lal 2016; Soussana et al. 2019) to reach Target 2.4 '*By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality*' and Target 15.3 '*By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world*'.

The spotlight on SOM is due to its benefits in agroecosystems, related to the three dimensions of soil quality and fertility. From a chemical perspective, SOM significantly contributes to the nutrient storage and supply capacity of soils, soil pH buffering capacity, and retention of pollutants or toxic elements (Barłóg et al. 2020); from a physical one, it contributes to the soil structure and thereby to ultimately control soil erosion, water infiltration and the water-holding capacity (Lal 2020); biologically speaking, it is a primary source of carbon (C)/energy for soil microorganisms and for the whole soil biota, which are key players in soil function, while soils are one of the largest reservoirs of biodiversity (Martínez-García et al. 2018).

In agroecosystems, SOC accumulation is dependent on the balance of biomass C inputs and C losses through mineralization, leaching, and erosion (Liu et al. 2006). Therefore, agricultural management practices influence SOC accumulation greatly (Basso 2022) for example soil tillage (Mazzoncini et al. 2016), management and fertilizer choices (Bhogal et al. 2018), crop residue management (Turmel et al. 2015) and crop rotations (Dal Ferro et al. 2020), including the integration of CCs between consecutive cash crops (Thapa et al. 2022). Despite great interest in the topic of increasing the SOC stock, there is still great uncertainty about the efficacy of some practices because of highly variable effects among and within practices (Chenu et al. 2019) due to site specific climatic and soil conditions, as well as the accuracy of scaling up results from the microcosm to plot, field or even basin scale (Dignac et al. 2017). For example, some works report greater efficacy of compost than digestate for a more rapid increase of SOC (Bhogal et al. 2018), as well as different contributions of CC species to the SOC stock (Higashi et al. 2014) and the irrigation management (Emde et al. 2021). Moreover, in recent years, low rainfall and high weather variability have accelerated SOM losses (Pérez-Guzmán et al. 2020) and increased the pressure on farmers when it comes to facing the challenge of increasing the SOC stock under climate change scenarios. As highlighted by the EIP-AGRI Focus Group 'Soil Organic Matter in Mediterranean regions', it is urgent to increase SOC in degraded soils (SOC < 1%) in the short term, especially in the upper soil layer. However, the SOC stock increase is highly dependent on the time span and pedoclimatic conditions (Tadiello et al. 2023) and not always observed in the short term in large-scale studies also adopting conservation agricultural practices (Camarotto et al. 2020). For this reason, it is necessary to develop integrated agronomic strategies able to increase the SOC stock within a short time that could be easily adopted by farmers, to increase their efficacy and scalability. Considering all the above reported aspects, an on-farm experimentation was designed.

On-farm experimentations are joint explorations in which researchers and others engage closely with farming realities to align with the ways farmers learn (Lacoste et al. 2022). In the present case, the on-farm experiment was co-designed with local stakeholders

(farmers and a land reclamation authority) to assess the combined effects of organic fertilization with different biomass sources (compost and digestate), cover crops and irrigation on the SOC stock in the short term.

Materials and methods

Site description

The experimental site (Fig. 1) was located in the demo farm "Podere Fiorentina" of the local Land Reclamation Authority (Consorzio di Bonifica Veneto Orientale – CBVO), in San Donà di Piave (45°38′13.10" N, 12° 35′ 55.00″E, 1 m a.s.l.), north-eastern Italy. The experimental area covered a surface 6.5 ha and was divided in two section – i) irrigated and ii) rainfed. The irrigated sector extended over 4.5 ha, was rectangular shaped and drained with subsurface pipes; the rainfed sector was triangular shaped and composed of four fields drained by a surface system based on ditches. The area falls within the Cfa class of the Köppen classification, with rainfall mainly concentrated in the months of spring and autumn, and frequent thunderstorms during hot-humid summers. Climate data from 1992 to 2022 collected from the Veneto region agency for environmental protection (ARPAV) showed an average annual rainfall of 966 mm and average temperature of 13.7 °C (average maximum and minimum temperatures of 19.1 and 8.9 °C, respectively). The month with the lowest average minimum temperature was January (−0.4 °C), while the month with the highest average maximum temperature was July (30.0 °C). The main physical and chemical soil characteristics for the topsoil layer (0–40 cm) of the experimental site at the start of the experiment are presented in Table 1. It is worth noting that the rainfed area was characterized by higher values of organic carbon, total Kjeldahl nitrogen (TKN) and phosphorus (P). The soil hydrological properties were similar across the experimental area, with a mean bulk density (BD) of 1.25 g cm^{-3}, a mean field capacity of 27.7% (v/v), and a mean wilting point of 8.5% (v/v) in the first 0–40 cm of soil.

Experimental layout and crop management

The experimental layout included 10 plots (0.3 to 0.9 ha). It was co-designed with the local Land Reclamation authority, namely Consorzio di Bonifica Veneto Orientale, and companies working on irrigation (Netafim), seed production (Seminart SRL and Corteva Agriscience ™) and organic matrices production (Bioman SPA) (Fig. 2); the second step consisted in presenting and discussing the concept idea with professionals and farmers during dedicated meetings.

The following variables were studied in the first two years of the experiment: two types of organic

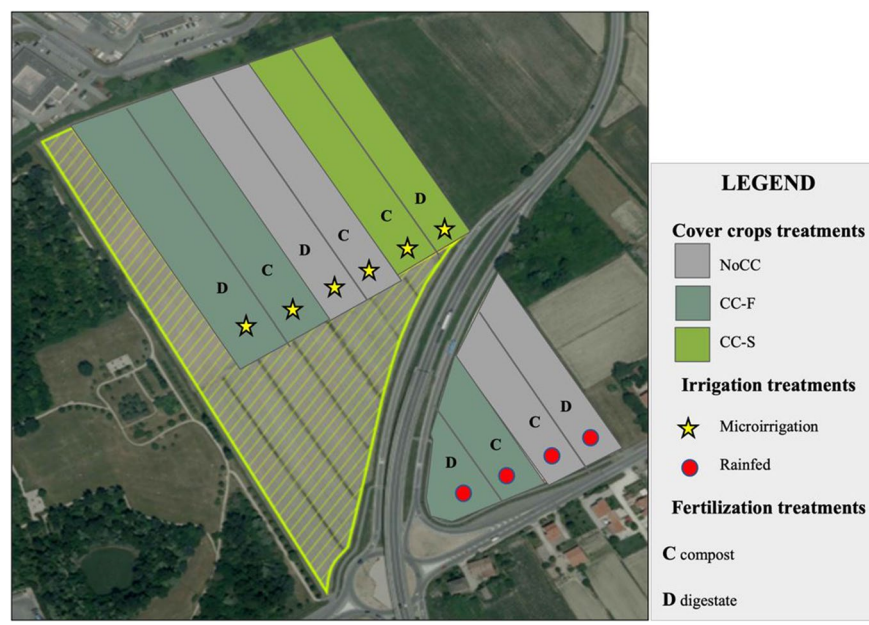


Fig. 1 Map of the "on farm experimentation"

Table 1 Average physico-chemical characteristics of the 0–40 cm soil profile at the beginning of the experimental period (average ± SE)

Soil variables	Field area		Method
	Irrigated	Rainfed	
Sand (%)	51.1 ± 1.0	47.6 ± 1.7	Standard sieve-pipette method (ISO 11277, 2009)
Silt (%)	25.6 ± 0.7	26.2 ± 0.6	
Clay (%)	23.3 ± 0.4	26.2 ± 1.1	
pH	8.14 ± 0.01	8.08 ± 0.01	Dual meter pH/conductivity (soil/water solution with ratio of 1:2.5)
EC (mS cm^{-1})	105.0 ± 0.8	109.5 ± 2.2	
Organic carbon (%)	0.85 ± 0.01	1.13 ± 0.02	CNS elemental analyzer
Inorganic carbon (%)	6.58 ± 0.03	6.34 ± 0.06	
Total Kjeldahl nitrogen (mg kg^{-1})	863.5 ± 15.0	1206.2 ± 25.2	Kjeldahl method
Total phosphorus (mg kg^{-1})	574.3 ± 8.7	706.0 ± 10.4	ICP-OES (Yang et al. 2018)
PO_4^{3-} (mg kg^{-1})	11.4 ± 0.5	18.5 ± 1.2	Ion chromatography system after soil water extraction
NO_3^- (mg kg^{-1})	1.43 ± 0.02	1.15 ± 0.02	



Fig. 2 Discussion about on farm experimentation among researchers and representatives of companies and stakeholders (Land Reclamation Authority, Netafim, Seminart SRL, Corteva Agricscience ™, Bioman SPA) involved in the participatory process

fertilizer: compost from pruning waste (C) vs. digestate from anaerobic digestion of manure (D); ii) two irrigation regimes: drip irrigation (I) vs. rainfed (R). The CC variable was added in the 3rd and 4th years, as follows: a fixed treatment (CC-F) with a species belonging to the Poaceae family (X *triticosecale*) kept constant throughout the experiment as well as a control without a CC (NoCC) in both irrigated and rainfed sections; a 2-year succession (CC-S) of 2 CC species belonging to the Brassicaceae and Poaceae families (*Sinapis alba* L.; *Lolium multiflorum* Lam.) (only in the irrigated section). The distribution of the experimental variables is listed in Table 2.

A grain maize-soybean cash crop succession was adopted throughout the 4 years of the experiment, with the following details: i) grain maize (Pioneer 937 - FAO 700) sown on June 5th 2019 and harvested on October 25th 2019; ii) soybean (var. P21T45) sown on May 9th 2020 and harvested on October 19th 2020; iii) grain maize (Pioneer 937 - FAO 700) sown on April 21st 2021 and harvested on September 23rd 2021; iv) soybean (Pioneer P 18A02) sown on May 11th 2022 and harvested on October 7th 2022. During April of each year, the seedbed preparation for all the cash crops was carried out in spring as follows: organic matrix application using a manure spreader, plowing (about 20 cm depth), subsoil tillage followed by rolling harrowing. During the 3rd and 4th years, CC mechanical termination was performed before organic matter distribution.

The quantity of organic matrices applied was calculated considering their N content and the maximum N application allowed by the regional law (DGR 25 of 2 March 2018). Thus, on yearly average, 9.8 Mg ha^{-1} and 19.0 Mg ha^{-1} of digestate and compost dry matter, respectively, were applied. The costs related to the different fertilization strategies (digestate, compost) was calculated considering cost of purchase, transport and distribution and were compared to those of mineral fertilization. The cost estimation for each fertilization strategy has been set *per* N unit.

During the cash crop cycle, weed control was performed chemically, using post-emergence

Table 2 Description of the integrated practices tested in the on-farm experimentation from 2019 to 2022

Treatment code	Agronomic practices			
	Organic fertilization 2019–2022	Irrigation 2019–2022	Cover crop 2020/2021	Cover crop 2021/2022
CC-F:D:I	Digestate	Microirrigation	Triticale	Triticale
CC-F:C:I	Compost	Microirrigation	Triticale	Triticale
NoCC:D:I	Digestate	Microirrigation	Fallow	Fallow
NoCC:C:I	Compost	Microirrigation	Fallow	Fallow
CC-S:C:I	Compost	Microirrigation	White mustard	Ryegrass
CC-S:D:I	Digestate	Microirrigation	White mustard	Ryegrass
NoCC:D:R	Digestate	Rainfed	Fallow	Fallow
NoCC:C:R	Compost	Rainfed	Fallow	Fallow
CC-F:C:R	Compost	Rainfed	Triticale	Triticale
CC-F:D:R	Digestate	Rainfed	Triticale	Triticale

Table 3 Compositions of the compost and digestate matrices each year

Years	Organic matrices	Dry Matter (%)	Corg (%dm)	N (%dm)	P (%dm)	K (%dm)
1st	Compost	80.0	24	1.9	0.93	2.12
	Digestate	29.2	53.4	2.4	1.39	2.43
2nd	Compost	71.0	29	2.1	0.43	2.11
	Digestate	23.1	52.8	2.9	1.02	3.45
3rd	Compost	75.0	23	1.9	0.64	2.03
	Digestate	20.5	52.8	3.2	0.59	2.22
4th	Compost	55.4	31	1.93	0.58	2.10
	Digestate	20.2	52.8	3.2	0.61	1.74

treatment for maize in 2019 and soybean in 2020, and a pre-emergence treatment for maize 2021 and soybean 2022. The main compositions of the compost and digestate are reported in Table 3, and irrigation and fertilization management are summarized in Tables 4 and 5.

The winter CCs were sown using a sod-seeding drill on November 5th 2020 and October 18th 2021 and terminated with a rotary mulcher on March 27th 2021 and April 8th 2022. Triticale (var. Titania) was sown with a seeding rate of 204 kg ha^{-1} in both years, whereas white mustard (var. Maryna) in 2020 and ryegrass (var. Suxyl) in 2021 were sown at 29 and 63 kg ha^{-1} seeding rates, respectively.

Data collection

All the data collections described from here on were carried out in collaboration among researchers, farmers and technicians from CBVO.

Table 4 Number of drip irrigation events and total amount of water (mm) applied each year

Years	Number of irrigation events	Total water applied (mm)
2019	4	77
2020	3	51
2021	10	173
2022	20	157

Cash crop (total aerial biomass and grain) and CC biomasses (including the weeds present within the CC biomass samples) were sampled each year at harvest and termination time in 3 georeferenced sampling points of 4 m^2 for each plot. The dry matter content was determined by drying the biomass in a thermo-ventilated oven at 65 °C until constant weight was registered. CC dried biomass was chopped and analyzed for its C content (only for CCs) using a CNS

Table 5 Average organic carbon (Corg), N, P_2O_5, and K_2O supplied by the organic matrices throughout the 4 years of the experimentation

Organic matrices	Corg (Mg ha^{-1} y^{-1})	N (kg ha^{-1} y^{-1})	P (kg ha^{-1} y^{-1})	K (kg ha^{-1} y^{-1})
Compost	4.9	369	128	291
Digestate	5.2	328*	79	137

*In the first year, 120 kg ha^{-1} were supplied as mineral N to reach the maize request while maintaining the same Corg supply from compost and digestate

analyzer (elemental analyzer Vario Max, Elementar Americas, Inc., DE). Fixed C was determined by multiplying its concentration for dry biomass produced per unit area. The protein contents of the maize and soybean grains were determined by near-infrared spectroscopy (NIRS) (Infratec-1241 instrumentation, Foss Analytical, Hillerød, Denmark).

Soil samples (0–20 and 20–40 cm depths) were collected with a drill at the beginning (March 2019) and at the end (November 2022) of the experiment, and then left to be air-dried outdoors in boxes for about 1 month. Each soil sample was composed by 4 subsamples (one for each square meter). The dried samples were sifted to 2 mm and analyzed for their SOC content using a CNS elemental analyzer (Vario Max, Elementar Americas, Inc., DE).

Organic carbon balance

The OC balance was estimated in the first 0–40 cm of the soil layer. The SOC stock variation was determined as follows:

$$SOC_{stock}\ (Mg\ ha^{-1}) = \left[SOC_{nov22}(\%) \times BD\ (g\ cm^{-3}) \times depth\ (cm) \times 0.1\right] - \left[SOC_{mar19}\ (\%) \times BD\ (g\ cm^{-3}) \times depth\ (cm) \times 0.1\right]$$

where $SOC\%_{nov22}$ and $SOC\%_{mar19}$ are the percentages of SOC determined in the soils sampled in November 2022 and March 2019, respectively (see paragraph 2.3), BD is the soil bulk density determined according to Rawls et al. (1992), and 'depth' is the monitored 0–40 cm soil layer.

The exogenous OC (from compost and digestate) was calculated considering the compost and digestate composition (Table 3) and the supplied quantity (Table 5). The endogenous OC from aboveground cash crop residues and belowground biomass production, including rhizodeposition, was estimated on the basis of total aboveground biomass at harvest time. Aboveground residue dry matter was evaluated at harvest time. Belowground biomass production was estimated to be 1.1 times and 0.2 times the dry matter residues of maize (Dal Ferro et al. 2020) and soybean (Nissen et al. 2008), respectively. The crop residues and root C content was estimated to be 45% of dry matter (Kätterer et al. 2011). Aboveground CC dry matter was measured at harvest time, and its C content was measured as reported in paragraph 2.3. On the basis of a previous experiment (data not shown), CC belowground biomass production was estimated to be 2.1, 1.3, and 1.1 times the aboveground dry matter of triticale and ryegrass, weeds, and white mustard, respectively. The C content of the belowground biomass was estimated to be 45% of the dry matter (Kätterer et al. 2011). The efficacy of organic C fixation was calculated as the ratio between the SOC stock variation and total organic C inputs (exogenous C + endogenous C).

Statistical analysis

Considering the variability of the physico-chemical parameters of the samples taken in the rainfed area of the farm versus the ones taken in the irrigated area before the beginning of the experiment (Table 1), the soil dataset was split in two subsets to avoid masking possible effects of the practices implemented in the experiment. Three permanent plots of 4 m^2 each were established for each of the ten combinations of treatments tested on the farm; they were distributed along a longitudinal transect at regular intervals from the field borders and between two consecutive fields. Each permanent plot was identified with the only purpose of sampling but was managed with the same field operation occurring in the relative field.

Statistical analyses of the above-listed variables were performed using RStudio software (Core Team R 2014). All the outcome variables were analyzed using linear models where the CC treatment, fertilization, irrigation and their interaction were used as fixed factors. Marginal and conditional residual distributions were checked visually to detect possible

issues of non-normality or heterogeneity of variances. An analysis of variance (ANOVA) of each model was performed and the Tukey's HSD test at $P < 0.05$ was used as post-doc analysis.

Results

Meteorological data

Yearly rainfall was above the 30-year average (996 mm) in the first year (2019, +206 mm), whereas it was lower in 2020 (−222 mm) and 2022 (−354 mm). The distribution of rainfall in 2019 showed high precipitation events concentrated in spring (249 mm in April and May on average) and the winter months of November and December (177 mm on average) (Fig. 3). In 2020, high precipitation were observed in June (206 mm), in September and October (132.9 mm on average), and in December (147 mm), after CC sowing. A similar precipitation distribution to 2019 was observed in 2021, when high precipitation events were recorded in spring (122 mm in April and May on average) right after CC termination, and in November (162 mm) after CC sowing. In 2022, the highest value of 138 mm was recorded in September, while an average of 113 mm was measured in November and December. The highest and lowest air temperatures were measured in July and January, respectively, confirming the pattern observed in the last 30 years. However, the yearly average maximum (19.9 °C) and minimum (9.4 °C) temperatures recorded during the experimental period were +4.2% and +5.6% higher than the average 30-year values, respectively. The distribution of monthly cumulative ET0 showed the lowest values from November to January (9.1 mm month^{-1} on average) throughout the 4 years, while the highest value was from June to August (137 mm month^{-1} on average).

Crop growth and grain quality

The crop aboveground biomass was significantly affected by the fertilizer in three out of four years (Table 6). Digestate application increased the aboveground biomass of maize in both growing seasons (+26.0% and +37.7%, in 2019 and 2021, respectively) compared with compost (6.05 ± 0.19 Mg ha^{-1} and 6.72 ± 0.60 Mg ha^{-1}, respectively). The same effect was observed for grain yield (+88.2% and +37.4%, in 2019 and 2021, respectively) compared with compost application (4.91 ± 0.24 Mg ha^{-1} and 4.07 ± 0.48 Mg ha^{-1}, respectively). The digestate significantly increased (+29.9%) the aboveground

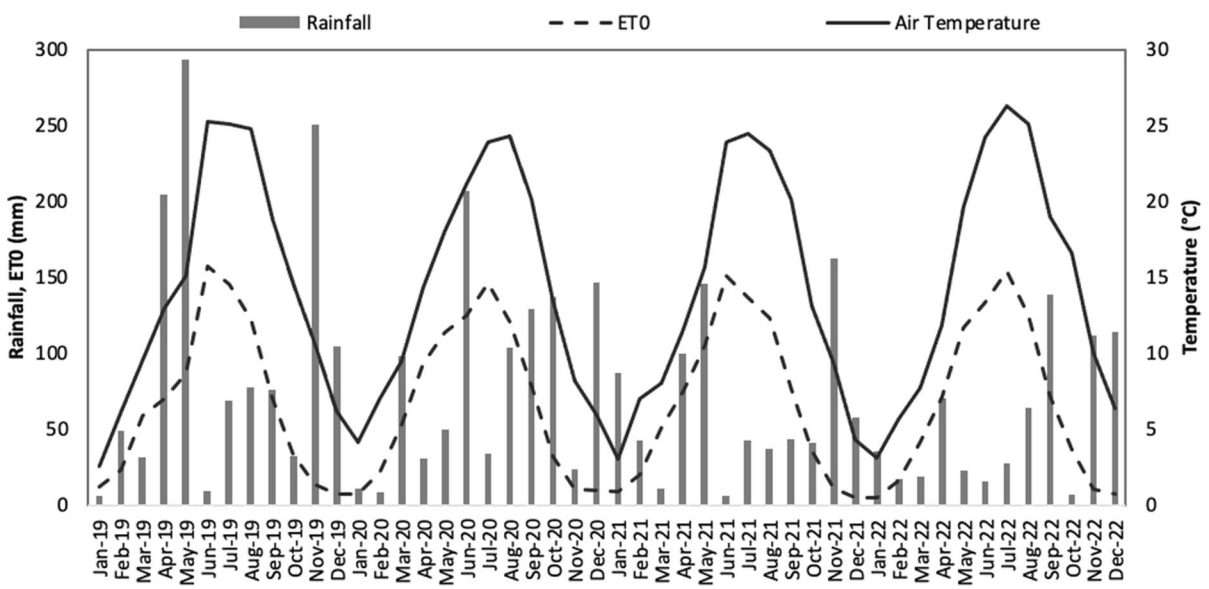


Fig. 3 Monthly rainfall, evapotranspiration (ET0) and mean air temperatures from 2019 to 2022 in Noventa di Piave (5 km from San Donà di Piave)

Table 6 ANOVA significance table showing the effects of fertilization, irrigation, and cover crop presence and type on maize and soybean growth and agronomic parameters

Source of variation	AB	GY	GP
Maize 2019			
F	**0.0009**	**<0.0001**	**0.0323**
I	0.6182	0.4880	0.2253
F x I	0.5391	0.7918	0.4172
Soybean 2020			
F	0.2112	0.4271	0.1693
I	0.1119	0.2398	**0.0034**
F x I	0.7844	0.1519	0.1238
Maize 2021			
CC	**0.0047**	**0.0268**	0.6697
F	**0.0101**	**0.0409**	0.6027
I	**0.0068**	**0.0018**	0.5391
CC x F	**0.0393**	0.2552	0.3257
CC x I	**0.0244**	**0.0356**	0.3726
F x I	0.0747	0.0824	0.6027
CC x F x I	0.3101	0.3565	0.8123
CC*	0.5041	0.7015	0.3879
F	0.5436	0.9904	0.9112
CC* x F	0.7388	0.9018	0.8466
Soybean 2022			
CC	0.3909	0.5168	0.2476
F	**0.0054**	0.7461	0.1236
I	**<0.0001**	**<0.0001**	0.2150
CC x F	0.4142	0.8600	0.1769
CC x I	0.9096	0.5703	0.3679
F x I	0.0529	0.0912	0.7766
CC x F x I	0.8951	0.4328	0.0717
CC*	0.2476	0.9118	0.1468
F	**0.0011**	0.7863	0.0962
CC* x F	0.4707	0.4285	0.7739

Significant p-values are reported in bold

AB aboveground biomass, *GY* grain yield, *GP* grain protein content, *F* fertilization (compost vs. digetate), *I* Irrigation (microirrigation vs. rainfed), *CC* cover crops (NoCC vs. CC-F), *CC** cover crops (NoCC vs. CC-F vs CC-S)

biomass of soybean compared with compost (2.88 ± 0.24 Mg ha^{-1}) only in the 4th year, but the fertilization treatment never influenced grain production (4.65 ± 0.12 Mg ha^{-1} and 2.05 ± 0.18 Mg ha^{-1} on average in 2020 and 2022, respectively).

Irrigation had a significant effect only in the 3rd and 4th years of the experiment, with opposite trends. In the 3rd year, maize aboveground biomass and grain yield were significantly higher under rainfed conditions than under irrigation (6.1 ± 0.8 Mg ha^{-1} vs. 3.8 ± 0.4 Mg ha^{-1}). Conversely, the aboveground biomass of soybean was significantly improved by irrigation compared with the rainfed condition in the 4th year (2.7 ± 0.1 Mg ha^{-1} vs. 1.0 ± 0.1 Mg ha^{-1}).

Considering the effect of management on grain yield in the 4 years, the integrated practices that involved digestate outperformed those based on compost, except when compost was used under irrigation and in the presence of CCs (Fig. 4). The introduction of irrigation in agronomic management had a significant effect in all 4 years only in the field under compost fertilization and CC-F (+16.2% for cumulative grain production).

The grain protein content was not significantly affected by the different factors throughout the experiment, except maize fertilization in 2019 (7.81 ± 0.14% and 8.23 ± 0.12% with compost and digestate, respectively) and soybean irrigation in 2020 (42.69 ± 0.14% and 43.33 ± 0.14% under irrigated and rainfed conditions, respectively).

Soil organic carbon

Soil organic carbon under irrigation management

Under irrigation management, the year, the CC, the fertilization x CC interaction and the year x fertilization interaction significantly affected the SOC content. In addition, SOC was significantly affected by the year x sampling depth x fertilization interaction (Table S.1). The highest increase in SOC was recorded in the topsoil layer (0–20 cm) under compost fertilization (+35.7%), then in the deeper soil layer (20–40 cm) (+18.5%) under the same management. Under digestate treatment, the SOC increase was not consistently different from the starting condition (Fig. 5).

Soil organic carbon under rainfed management

Under rainfed conditions, the OC content was significantly affected by the year, the CC, the year x CC x fertilization interaction and the CC x sampling depth x fertilization interaction (Table S.2). As for the effect of the year x CC x fertilization interaction on the OC content, the highest value was recorded at the end of the experiment under compost fertilization in the absence of a CC. At the end of the experiment, the OC content was almost similar in

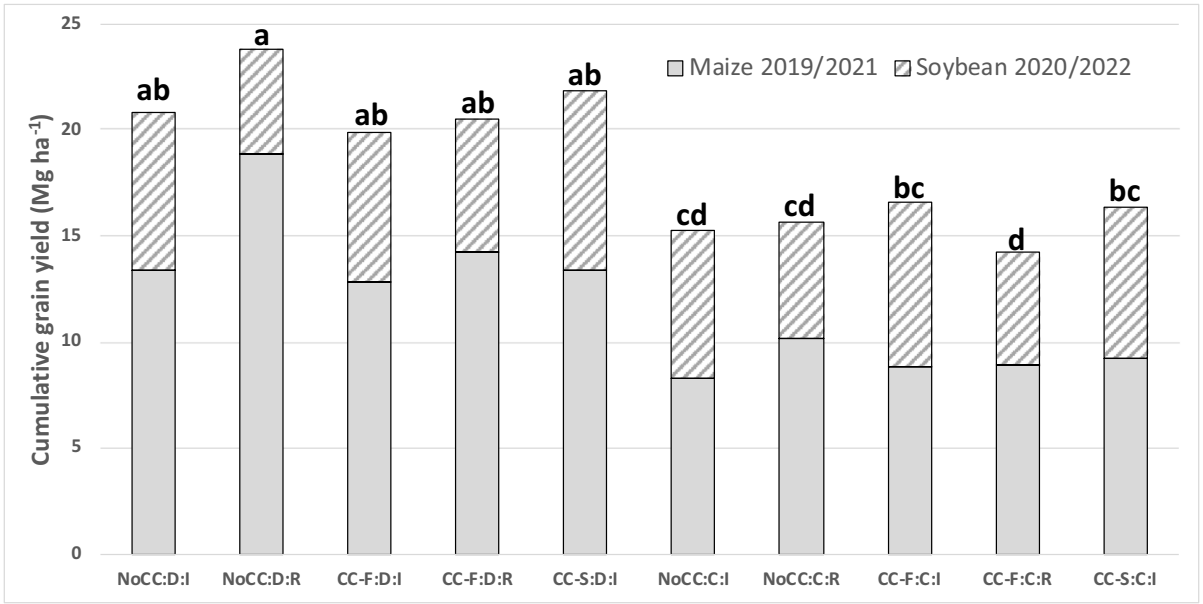


Fig. 4 Four-year cumulative grain yield (Mg ha^{-1}) following the ten tested management practices, and common district yield as a comparison. Different letters indicate significant differences at $p < 0.05$ (Tukey HSD test)

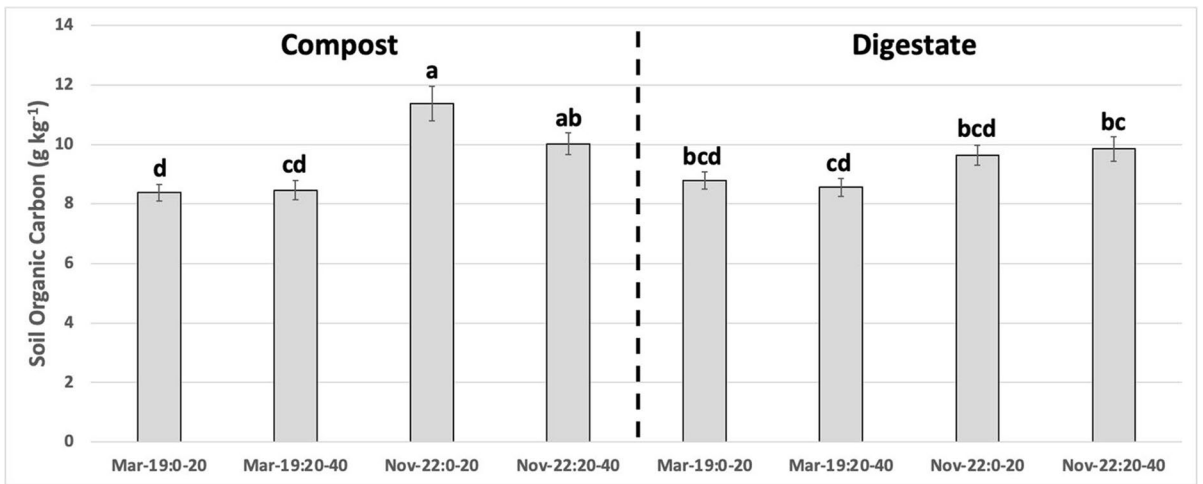


Fig. 5 Soil organic carbon content (g kg^{-1}) with the two organic fertilizers at different times of the experiment (beginning: Mar-19; end: Nov-22), in soil sampled at two depths (topsoil: 0–20; deep soil: 20–40 cm) under irrigation management. Different letters indicate significant differences at $p < 0.05$ (Tukey HSD test). Vertical bars, standard errors

all the other CC and fertilization combinations and close to the content found at the beginning of the experiment. The only consistent improvement was found under compost fertilization in the plot without a CC and under digestate fertilization with CC-F (Fig. 6).

Carbon budget

The cumulative OC input was significantly different among the ten integrated practices due to different endogenous OCs (Table 7). The exogenous OC supplied by organic fertilization was similar in

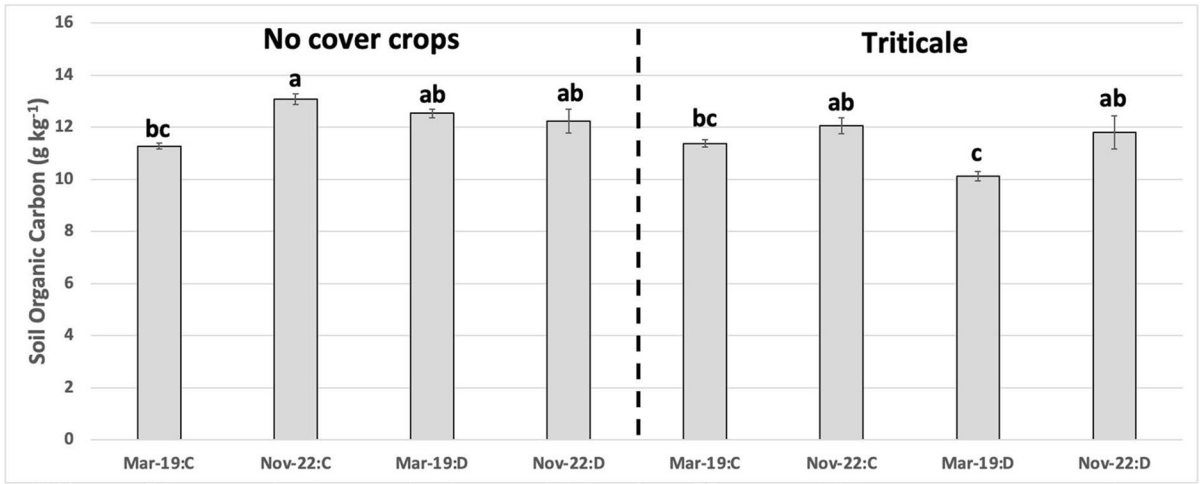


Fig. 6 Soil organic carbon content (g kg^{-1}) under rainfed management with different cover crop management practices at different times (beginning: Mar-19; end: Nov-22) and with the two organic fertilizers (digestate: **D**; compost: **C**). Different letters indicate significant differences at $p < 0.05$ (Tukey HSD test). Vertical bars, standard errors

the compost (19.4 ± 1.0 Mg ha^{-1}) and the digestate (20.9 ± 1.4 Mg ha^{-1}), whereas different cash crop residue and CC biomasses were measured among the integrated practices (Table 7). Exogenous OC represented 44.5% (NoCC:D:R) to 56.1% (CC-F:C:R) of the cumulative OC input. After 4 years, the SOC stock increase ranged from −1.2 Mg ha^{-1} (No-CC:D:R) to 10.3 Mg ha^{-1} (CC-S:C:I), corresponding to OC fixations of −2.9% and +27.8%, respectively. Considering the main effects combined in the ten integrated practices, it was observed in the short term that: i) irrigation significantly increased the SOC stock ($+7.2 \pm 0.7$ Mg ha^{-1}) compared with the rainfed condition ($+ 4.0 \pm 1.2$ Mg ha^{-1}); ii) cash crop fertilization with compost significantly increased the SOC stock ($+7.8 \pm 0.8$ Mg ha^{-1}) compared with digestate ($+ 4.0 \pm 0.9$ Mg ha^{-1}); iii) the introduction of CCs and their management did not have any effect

Table 7 Changes in SOC stock and fixed organic carbon (OC) measured under different integrated practices. Estimated SOC accumulation rates based on the "4 per 1000" initiative in the topsoil (0–40 cm)

Treatment	Exogenous OC (Mg ha^{-1})	Endogenous OC (Mg ha^{-1})				Cumulative supplied OC (Mg ha^{-1}) (1)		ΔSOC stock (0–40 cm) (Mg ha^{-1}) (2)		Fixed OC (1:2 ratio) (%)		*"4 per 1000" check* (Mg ha^{-1})
		Cash crops		Cover crops								
	2019–2022	2019–2022		2021–2022		2019–2022		2019–2022		2019–2022		2019–2022
CC-F:D:I	21.5	17.4	ab	2.5	ab	39.6	ab	5.7	abc	13.9	ab	0.613
CC-F:C:I	19.7	15.0	b	2.1	bc	35.3	b	9.3	a	25.1	a	0.675
NoCC:D:I	20.4	19.2	ab	1.4	bc	39.9	ab	4.7	abc	12.0	b	0.622
NoCC:C:I	18.8	14.9	b	0.2	c	33.8	b	9.4	a	27.6	a	0.569
CC-S:C:I	20.9	16.8	ab	1.3	bc	38.1	ab	10.3	a	27.8	a	0.638
CC-S:D:I	20.2	18.5	ab	1.6	bc	39.2	ab	3.5	bcd	9.1	bc	0.699
NoCC:D:R	19.3	23.8	a	1.4	bc	43.4	a	−1.2	d	−2.9	c	0.904
NoCC:C:R	18.4	16.4	b	1.6	bc	35.2	b	7.3	abc	21.0	ab	0.822
CC-F:C:R	19.3	14.3	b	2.9	ab	34.5	b	2.8	cd	8.1	bc	0.829
CC-F:D:R	23.0	19.0	ab	4.3	a	43.2	a	7.0	abc	15.1	ab	0.745

CC-F fixed treatment (X *triticosecale*), *CC-S* succession treatment (*Sinapis alba* L.; *Lolium multiflorum* Lam.), *NoCC* no cover crop, *D* digestate, *C* compost, *I* drip irrigation, *R* rainfed

on the SOC stock. All integrated practices but the NoCC:D:R condition reached the "*4 per mille*" goal.

Discussion

Soil organic carbon

Among the tested practices, compost addition under irrigation management contributed to the most consistent SOC content increase in the topsoil (0–20 cm depth) compared to digestate. This can be mainly explained by the different contributions of the different materials and ensuing organic matter stability levels. Compared with compost addition, digestate addition to the soil provided easier available organic matter, mostly degradable in the short term (Alburquerque et al. 2012). Martínez-Blanco et al. (2013) showed that C sequestration following compost application was higher in the short term (up to 40% of the applied C) and decreased down to 2–16% over a 100-year period. In our study, average C sequestration following compost addition was 21.9% after 4 years.

Irrigation improved the SOC stock in the 0–40 cm layer, in accordance with Emde et al. (2021) on the basis of 47 case studies located all over the world. The CCs were introduced only in the second two-year period of experiment. They contributed to increase the SOC content depending on the CC species and the quality of its biomass (e.g., C:N ratio), and returned to the soil more than the sole cover crop C (Higashi et al. 2014; Sias et al. 2021). As already reported by other authors (Jian et al. 2020; Qin et al. 2023), although the CC-F condition returned 2.1 times more C to the soil than the other conditions, its contribution in terms of SOC storage in the first 0–40 cm was only 89% that of the CC-S condition. However, we did not observe a consistent effect of CCs on the SOC stock increase in the first 0–40 cm soil layer. This confirms that the time since CC introduction (Poeplau and Don 2015) and CC biomass production (Duval et al. 2016) are key aspects of SOC stock changes.

In order to meet the aim of many of the farmers of the area where the on-farm experimentation was implemented, that is maximizing the SOC stock within the shortest possible period, the most promising management strategy should integrate fertilization with compost and irrigation independently from the adoption of CCs during the fallow period.

Side effects

Although the aim of the study in terms of SOC stock increase was reached, the short-term sustainability of the grain yield of both cash crops throughout the 4 years of the experiment should be considered.

From a merely productive perspective, the strategy solely based on organic fertilization led to an overall maize grain yield loss compared to the production level that can be attained in the same rural district in farms adopting adequate fertilization based on chemical inputs (5.9 Mg ha^{-1} in this study vs. 12.7 Mg ha^{-1} on average in 4 farms). This result can be attributed to the mismatch between N release from organic fertilizers and N uptake by maize, especially when compost is used, and could deter farmers from using these sources of fertilization. A possible solution might be mixed fertilization to combine the targets of soil organic matter increase and satisfactory yields (Maucieri et al. 2019). Contrary to maize, the soybean grain yield was similar to the production level of the farms of the district (3.4 Mg ha^{-1} in this study vs. 3.1 Mg ha^{-1} on average in 7 farms) (Table S.3) due to its capability to fix N. In addition to yield loss, costs related to organic fertilization must be considered. Indeed, adding costs for purchase, transport and distribution, organic fertilization was more expensive than the mineral one (+12% for compost and + 20% for digestate).

The higher productivity of maize under digestate fertilization can be explained by the different natures of the two organic fertilizers (Tambone et al. 2010), and different mineralization rates – a variable that can determine different amounts of N release during the cash crop growing cycle (Di Mola et al. 2021; Farneselli et al. 2022; Tambone and Adani 2017; Zaccardelli et al. 2021;). In addition, the highest grain yield recorded in the 1st year of the experiment could be related to the additional amount of N supplied through urea, in order to align the quantity of N supplied in the field managed with the two different organic fertilizers to maintain the supplied OC constant.

Irrigation significantly supported the cumulated crop grain yield when combined with compost fertilization and CC-F with triticale. Conversely, irrigation did not have the same effect on crop production under digestate fertilization combined with the same CCs (CC-F). Those results could be explained by the stimulation effect of irrigation on soil microbial activity and soil organic matter mineralization when less N is available.

Conclusions

An on-farm experimentation was co-developed with local farmers and a land reclamation authority to answer their specific aim of increasing SOC within a short time. Almost all strategies increased the SOC content and stock. Considering the results, the most promising management strategy should integrate organic fertilization with compost and crop irrigation, independently from CCs during the fallow period. However, the potential of CCs to enhance the SOC stock should be further investigated, as previous studies have reported promising long-term results.

Although the SOC stock increase within a short period was achieved, a question still remains open about the lower productivity of maize when solely fertilized with organic sources of N.

Our findings suggest that SOC accumulation is achievable in the short term with abundant applications of organic biomass, but the strategy might lead to economic losses (lower maize productivity).

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