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Italian Journal of Agronomy 2022; volume 17:2114

Organic *versus* conventional farming: Medium-term evaluation of soil chemical properties

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Highlights

- *Organic management did not increase soil organic carbon content 14 years after the system was established.*
- *The soil organic carbon was stable over time in the conventional system.*
- *Soil organic nitrogen was higher in the organic farm than in the conventional farm.*
- *Soil C/N ratios in organic and conventional management were <10, indicating active mineralization.*

Abstract

Agricultural management affects soil fertility through the frequency and type of agronomic practices such as mechanical operations, type and rate of fertilizers, crop rotations, and residue management. This study evaluated the evolution of soil chemical properties (pH; electrical conductivity; soil organic carbon, SOC; total Kjeldahl nitrogen, TKN; and available phosphorous, PO_4-P) over time in two farming systems, organically and conventionally managed, after 5 and 14 years after the establishment of both systems, in northeastern Italy. SOC content remained stable in the conventional farming system, but slightly decreased in the organic farming system, despite inputs from organic amendments. In contrast, soil TKN remained consistently higher in the organic farming system. The PO_4-P increased over time, in both farming systems. Moreover, we observed that an increase of 1% in soil clay content resulted in increases of 0.0534 and 0.0053 g kg^{-1} in SOC and TKN, respectively. In conclusion, our results indicate that organic management does not have an advantage over conventional management in terms of soil organic matter accumulation.

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Key words: Soil fertility drivers; soil organic matter; soil chemical properties.

Acknowledgements: the authors are thankful to Pierluigi Franchin, Andrea Di Bernardo and Paolo Cadin for their support in farm management data collection, as well as to the other technical and research staff of the farm that assisted in soil sampling and analysis.

Received for publication: 6 June 2022.
Revision received: 10 August 2022.
Accepted for publication: 23 August 2022.

Italian Journal of Agronomy 2022; 17:2114
doi:10.4081/ija.2022.2114

Introduction

Soil quality is a crucial topic for the future of agriculture because the ability of soil to support plant growth depends on the interactions between soil physical, chemical, and biological properties. Additionally, human health and well-being are closely connected with soil (Brevik *et al.*, 2020). Therefore, soil plays an important role in future agricultural policy, environmental protection, and climate change (Montanarella, 2020). Knowledge of soil dynamics is necessary to prevent soil quality decline, especially in terms of soil organic matter (SOM) content and nutrient availability. The former is highly correlated with soil physical characteristics, whose deterioration can reduce soil quality, increasing the risk of desertification. While soil nutrient availability can greatly influence crop production in the short term (Grilli *et al.*, 2021).

To obtain robust data on the evolution of soil quality, medium- to long-term experiments are essential to monitor slow-changing properties (Hartemink, 2006; Berti *et al.*, 2016). Some physical, chemical, and biological characteristics of soil have been proposed to be sensitive and consistent indicators of changes in soil quality (Cano *et al.*, 2018). Although defining suitable indicators of soil quality is complicated by the need to consider multiple functions of soil, a minimum dataset with a list of indicators for soil quality assessment has been proposed by Doran and Parkin (1997). Soil physical characteristics (*i.e*., texture, structure, porosity, mechanical resistance to penetration, and water infiltration capacity) have been used as starting points to evaluate the overall soil quality (Cavalcante *et al*., 2021). Among chemical properties, soil fertility can be assessed through soil pH, electrical conductivity (EC), soil organic carbon (SOC), total Kjeldahl nitrogen (TKN), available phosphorous (PO_4-P), and other nutrient levels (Hartemink, 2006). Several studies have investigated the correlations between physical and chemical soil parameters, showing that clay content is positively correlated with SOC at different spatial scales (Burke *et al*., 1989; Kaiser and Guggenberger, 2000; Zinn *et al*., 2007; Fiorini *et al*., 2020), sand content is negatively correlated with SOC in tilled soils (McLauchlan, 2006), and SOC content has a strong positive correlation with soil N content (Nardi *et al*., 2004). One of the main drivers of soil quality is the type of farming system (Dubois, 2011; De Valença *et al*., 2017), which impacts SOM concentration (Montanarella *et al*., 2015). The widespread use of mineral fertilizers in recent decades has increased crop yields, but the replacement or reduction in organic inputs has negatively influenced SOC content (Singh, 2018). Tillage and mechanical farm operations are responsible for SOC depletion because they mix and aerate the soil, stimulating microbe-driven SOM mineralization (Nardi *et al*., 2004; McLauchlan, 2006).

Organic farming has been proposed to improve soil quality (Willer and Sahota, 2020). The expansion in organic farming in recent decades has renewed the importance of understanding the effects of agricultural management on soil. However, no unique effects of farm management on soil characteristics have been reported because the overlap in management practices among farming systems makes broad generalizations difficult (Reeve *et al*., 2016). This suggests that management practices are more important than farming systems (*e.g*., conventional and organic) in terms of their impact on soil characteristics. Indeed, these effects are strongly related to the different frequencies and types of agronomic practices, such as the type and rate of fertilizer applications (Kurki *et al*., 2021), mechanical operations, crop rotations, residue management, and cover crops. Dal Ferro *et al*. (2017) highlighted that organic farming systems require a higher number of mechanical operations for weed control and reduce yield. Due to the yield gap and the reduction in the number of crops harvested in the rotation, the productivity of organic farming can be 29% to 44% lower than that of conventional farming, depending on the crops included in the rotation (Alvarez, 2021). Lower productivity leads to a lower quantity of crop residues left in the soil, which might negatively affect the accumulation of organic matter. Watson *et al*. (2002) reported that, in conventional and organic systems, the quantity and quality of crop residues (*e.g*., C/N ratio) influence the build-up of SOC and warned that N limitations in organic systems may decrease the amount of N returned to the field with crop residues, negatively impacting productivity in the following crop cycle. In a meta-analysis, Tuomisto *et al*. (2012) confirmed these results, showing that organic yields of individual crops are on average 75% of their conventional counterpart, mainly due to nutrient deficiencies, especially N. Several studies have reported a positive effect of organic farming on soil quality (especially increased SOM) (Reeve *et al*., 2016). However, organic farming can negatively influence the quantity of SOM in soil (mineralization due to the higher mechanical operations) and the organic matter supplied through crop residues due to the lower crops yield. Gosling and Shepherd (2005) compared the total SOM, total nitrogen, and C:N ratio from soils of agricultural fields managed organically and conventionally for a minimum of 15 years did not observe significant differences. However, they observed significantly lower concentrations of exchangeable potassium and extractable phosphorus in organically managed soils. These studies show that management practices impact soil fertility and should be considered by farmers, land managers, and crop advisers in the decision-making processes to choose appropriate agricultural practices (Sofo *et al*., 2022).

Although several studies have compared conventional and organic farming systems, few have been conducted in real farming conditions and most focused on crop yield. Few studies have conducted long-term monitoring or included results on soil characteristics. Therefore, our study aims to evaluate the evolution of soil chemical properties (pH, EC, SOC, TKN, and PO_4-P) over time in two farming systems (organically and conventionally managed), 5 and 14 years after the consolidation of the cultivation protocol.

Materials and methods

Experimental sites

This study was conducted at the experimental farm 'L. Toniolo' of the University of Padua, northeastern Italy. The farm includes two separate farming sectors (hereafter simply called 'farms'): an i) organic farm (OF); and ii) conventional farm (CF). The OF extends for approximately 12.5 ha in the Pozzoveggiani area in the Padova municipality (45°20´42' N, 11°54´39´ E; 7 m a.s.l.) and the CF for approximately 42 ha in Legnaro (45°21´00´ N,11°57´02´ E; 7 m a.s.l.) (Dal Ferro *et al*., 2017). These areas are on the flat area of the alluvial Po Valley, approximately 3 km apart, and are managed by the same technical supervision (Figure 1). The conditions of the geomorphology, farming systems, and landscape were similar for both areas. The water table fluctuates during the year from approximately 0.5 to 1.5 m in the cold season and approximately 1.5 to 3 m, or lower, during the summer. The climate is sub-humid, with a mean annual temperature of 13.5°C, classified as a humid subtropical climate (Cfa) (Beck *et al*., 2018). The mean annual rainfall is approximately 830 mm (1994-2021), and evapotranspiration usually exceeds rainfall from April to September by an average of 260 mm (Berti *et al*., 2014). Both study areas have a fluvic calcaric Cambisol (IUSS Working Group WRB, 2014). The soil of our experimental sites has an average bulk density of 1.45 Mg m^{-3}, high total calcium carbonate proportion ($CaCO_3$, approximately 26%), low natural fertility due to low organic matter content (approximately 15 g kg^{-1}), and low cation exchange capacity.

Management of organic and conventional farming systems

Since 2003 the OF area has followed a strict maize (*Zea mays* L.) - wheat (*Triticum aestivum* L.) - soybean (*Glycine max* (L.) Merr.) three-year rotation, arranged to permit the presence of all three crops in different plots during the same year. Agronomic field operations before sowing include mouldboard plowing to a depth of 30 cm followed by seedbed preparation with a disc harrow. Spring crop (maize and soybean) residues are incorporated during plowing, while wheat straw is harvested for use as livestock bedding and finally returned to the field as farmyard manure. Weed control of spring crops before sowing is mechanically conducted using the stale seedbed technique (according to climatic conditions over the years), whereas throughout the season, it is generally accomplished by smoothing harrow and hoeing operations. Spring crops are occasionally irrigated at volumes of approximately 40 mm per irrigation event. Farmyard manure (on average on fresh weight, C=90 g kg^{-1}, N=6 g kg^{-1}, P=1.6 g kg^{-1}, K=8.6 g kg^{-1}; 20% dry matter) produced within the farm was the main fertilizer used for soybean and maize whereas sugar beet vinasse (on average on fresh weight, C=81 g kg^{-1}, N=25 g kg^{-1}, K=50 g kg^{-1}; 32.5% dry matter) was the main fertilizer used for wheat (Tables 1 and 2).

The CF area does not follow a strict rotation and has been cultivated with maize, wheat, soybean, and sugar beets (*Beta vulgaris* L.). Agronomic field operations for seedbed preparation are similar to those for OF, with mouldboard plowing (to 0.35 m) followed by harrowing before seeding. Maize, soybean, and wheat residues are

Table 1. Crops nutrient application rates over the time frame of the study organized by management system (average ± standard deviation).

Crop	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})
Organic farming			
Maize	242.3±34.4	148.3±21.0	418.4±59.4
Soybean	136.5±44.4	83.5±27.2	260.7±79.7
Wheat	117.3±29.8	49.6±0.0	272.5±58.2
Weighted average	165.4	79.4	305.8
Conventional farming			
Maize	348.5±109.8	136.6±61.4	231.3±159.0
Soybean	0.0	64.4±8.0	100.0±0.0
Wheat	169.2±13.8	90.5±12.8	90.5±12.8
Sugar beet	190.3±75.1	55.6±0.3	166.7±53.4
Weighted average	227.8	102.6	162.9

Table 2. Cumulative fertilizers and carbon supplied over the time frame of the study.

Fertilizers	8 year cumulative supply (Mg ha^{-1})		Fertilizers C content (%)	8 year cumulative C supp (Mg ha^{-1})	
	OF	CF		OF	CF
Manure	172.9	26.8	9	15.6	2.4
Slurry	-	159.1	4.2	-	6.7
Sugar beet vinasse	9.8	-	8.1	0.8	-
Other organic fertilizers	0.3	-	40	0.1	-
Chemical fertilizers	0.1°	4.7	20#	-	0.4
Total				16.5	9.5

OF, organic farm; CF, conventional farm. °Potassium sulphate, admitted in organic farming; #the value is referred to urea added in the CF.

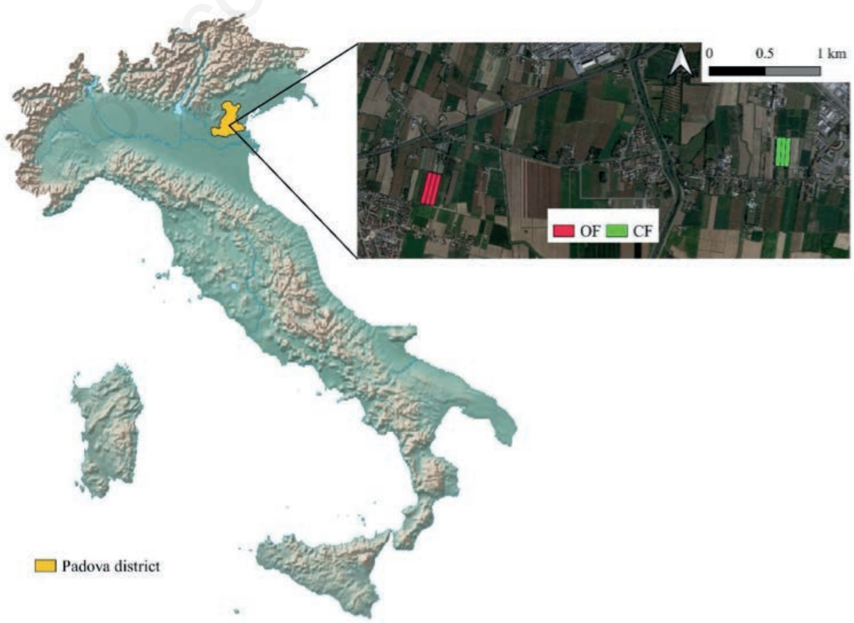

Figure 1. The location of the experimental sites. OF, organic farm; CF, conventional farm.

managed as in OF. For sugar beets, present only in the CF area, the seedbed is prepared as for other crops and residues are buried after crop harvest. Pests and weeds are controlled by agrochemicals according to the crop and seasonal trends. They generally include: i) for wheat, post-emergence tribenuron methyl and strobilurin-based compounds for weed control and rust disease; ii) for maize, a pre-emergence mix of S-metolachlor, terbuthylazine, and mesotrione; and iii) for soybean, post-emergence imazamox. Irrigation is occasionally performed on maize and soybean at volumes of approximately 40 mm per irrigation event. Wheat fertilization (Table 1) includes NPK application in autumn and N topdressings as urea and/or ammonium nitrate in late winter and spring. Maize fertilization generally consists of cattle slurry produced in the farm (C=42 g kg^{-1}, N=2.8 g kg^{-1}, P=0.6 g kg^{-1}, K=2.0 g kg^{-1}, 10% dry matter) in autumn or spring, just before ploughing, and one topdressing application of urea during inter-row hoeing (Table 1). Sugar beet fertilization is performed using potassium sulphate, triple super-phosphate, urea, and ammonium nitrate (Table 1). Soybean fertilization consists of two split applications: triple superphosphate at sowing and potassium sulphate in spring (Table 1).

In summary, the differences between OF and CF management included pest and weed management; mechanization; crop types and varieties; and rates, timing, and source of fertilization. The comparison presented in this paper uses soil samples taken in 2008 and 2017. In this period, the average yearly N and P_2O_5 supplied in CF were 37.7% and 29.2% higher, respectively, than those supplied in OF, while the K_2O input was 87.7% higher in OF than in CF (Table 1). The eight-year cumulative carbon supplied with fertilization was 73.7% higher in OF than in CF (Table 2).

Soil sampling and chemical analysis

Plots of 25 m wide × 250 m long were delineated in three fields on each farm to collect soil samples in georeferenced positions, allowing soil evolution to be compared over time. These were referred to as OF1, OF2, and OF3 for OF and CF1, CF2, and CF3 for CF. Within each plot, soil samples from a depth of 0-25 cm were collected in February/March of 2008 and 2017. In each plot, the soil samples were collected using a grid of 7.5 × 25 m in 2008 and a grid of 7.5 × 50 in 2017 for a total of 40 and 20 samples in 2008 and 2017, respectively. Each sampling point was georeferenced (Figure 2). The soil samples were air-dried and crushed to 2 mm using an electrical mill. Skeleton was absent.

Soil texture analyses were performed in the laboratory (pipette method) and the soil was classified according to the USDA classification method. The chemical analyses included pH, EC, SOC, TKN, and PO_4-P. pH and EC were determined in a solution with a soil/water ratio of 1:2.5 using a pH meter and an electrode (SevenMulti pH/conductivity meter, Mettler Toledo, Greifensee, Switzerland), respectively; SOC was determined using the Walkley-Black method; TKN was determined using the Kjeldahl method; and available PO_4-P was determined using the Olsen method.

Statistical analysis

Soil data were analysed using mixed-effect (hierarchical) models, separately for each chemical property (outcome variable). A nesting structure (random effects) was used to account for the interdependence of observations, sampling points within the same field as spatial pseudo-replicates, and samples from 2008 and 2017 as repeated measurements. Additionally, clay was used as a candidate covariate (fixed effect). These choices were made to obtain unbiased estimates of the fixed effects of interest. The fixed effects of interest were: i) farm type (OF or CF); ii) year (2008-2017); and iii) interaction between farm and year. Specifically, several models of different complexity in the fixed effect part were built, ranging from the full model that included all fixed effects (clay, farm, year, interaction between farm and year) to the null model that included only random effects and no fixed effects. All the models were compared using the Akaike information criterion (AIC, that balances goodness of fit and model complexity), to select a single final model for each chemical property. The final model (lowest AIC) was refitted using restricted maximum likelihood to obtain definitive unbiased estimates of the fixed effects. Marginal and conditional residual distributions were visually checked in the final model to detect possible issues of non-normality or heterogeneity of variances. If issues were found, the original data were transformed, the models were refitted, and the residuals of the new final model were checked. Issues were observed for PO_4-P but were solved by logarithmic transformation. The procedure used to build the hierarchical structure and select the best model was primarily based on Crawley (2007) and Onofri *et al*. (2016). Wald test ANOVA was used to confirm the final model results and post-hoc analysis was carried out to summarize the results in an easily interpretable way. For simplicity, only the results of the post-hoc analysis of the final model (after model selection with AIC) were reported. For farms, years, and their interaction, contrast plots showing the mean and standard error of the mean were drawn when the fixed effect was significant. Results of pairwise or multiple comparisons (with Tukey adjustment) are represented with letters (different letters = significant difference, same letters = non-detectable differences). Relationships with the clay covariate (if significant) were represented in a scatterplot with a regression line and its 95% confidence interval. All statistical analyses were carried out in *R* (R Core Team, 2021) using the following interdependent packages: *lme4* for building the mixed models (Bates *et al*., 2015), *DHARMa* for residual diagnostics (Hartig, 2021), and *emmeans* for post-hoc comparisons (Lenth, 2021).

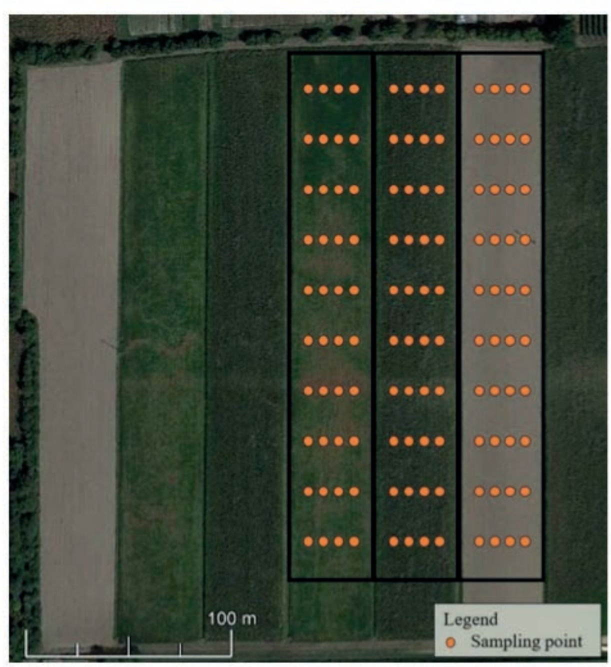

Figure 2. Sampling design in 2008.

Results and discussion

Soil physical properties

Soil from both sites had a loam texture with sandy veins present in some fields, such as OF2 and CF2, as shown by the higher percentage of sand (Table 3). Such textural characteristics are typical of this agricultural area, as indicated by the soil thematic maps of the Veneto Region Agency for Environmental Prevention and Protection (ARPAV) (http://geomap.arpa.veneto.it/maps/123/ view).

Soil chemical properties

In both management sectors, the pH was generally neutral/weak alkali, ranging from 7.06 to 7.85. Although the pH values were generally steady, significant differences were observed according to the interaction between year and management system (Figure 3A). The pH value increased by 2.6% in CF from 2008 to 2017. Additionally, significant differences in pH were found between CF and OF in 2008 and 2017: in OF, pH was higher than in CF in 2008 but lower in 2017. Several studies reported that soil pH increases under organic management (Drinkwater *et al*., 1995; Clark *et al*., 1998; Fließbach *et al*., 2007; Suja *et al*., 2017; Kiboi *et al*., 2020). However, in our OF system, we observed a decreasing trend for SOC and pH. As reported by Nardi *et al*. (2004), soil acidification can be related to the SOM mineralization process, which produces nutrient elements (in particular NH_3) whose oxidation may contribute to H^+ production.

Sugar beet vinasse and slurry may increase salt concentrations in the soil (Moran-Salazar *et al*., 2016; Dionisi *et al*., 2020), as does the excessive application of manure (Yilmaz and Alagöz, 2010). Even though these materials were used in our study, we did not notice any significant difference in EC depending on the sampling year or farm management, probably due to the salt leaching after rainfall events. The soil EC values ranged from 0.12 to 0.4 mS cm^{-1}, in line with the average values of loam and sandy loam soils in the area (Nardi *et al*., 2004), and guaranteeing no salinity risk (ARPAV, 2007).

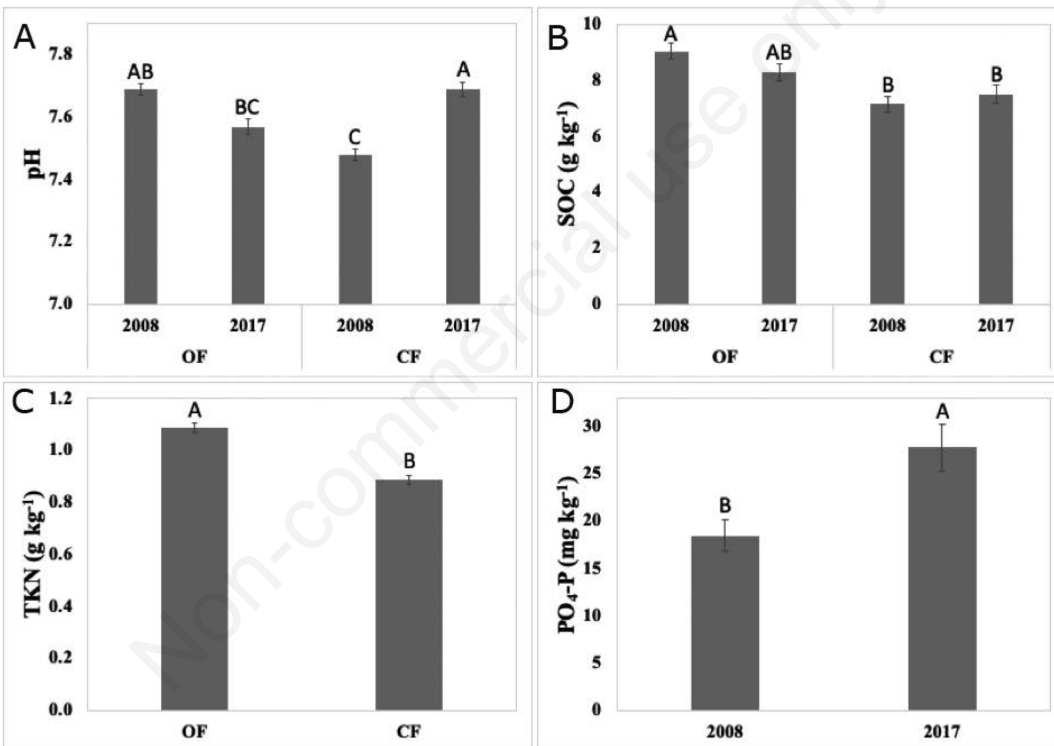

Figure 3. Average response of the chemical variables to farm management (OF, organic farm; CF, conventional farm) and sampling year, as estimated from the selected mixed effect model: A) soil pH; B) soil organic carbon (SOC); C) total Kjeldahl nitrogen content (TKN); D) soil available phosphorus (PO_4-P) content (mean±standard error). Different letters indicates significant differences at P<0.05, after Tukey's correction for multiple *post-hoc* comparison.

Table 3. Soil texture and standard deviation from data collected in the three fields of each management system are classified according to USDA (average ± standard deviation).

Management system	Field	Texture	Sand (%)	Silt (%)	Clay (%)
Organic farming	O1	Loam	35.17±3.77	46.93±3.07	17.90±2.39
	O2	Sandy loam	52.08±5.87	32.40±6.08	15.52±2.12
	O3	Loam	37.44±4.63	46.22±3.46	16.34±3.26
Conventional farming	C1	Loam	45.82±8.25	41.77±6.98	12.41±3.50
	C2	Sandy loam	58.44±8.46	28.06±5.61	13.50±4.18
	C3	Loam	45.63±8.66	39.01±5.73	15.35±3.20

Soil organic carbon in 2008 differed between the two management systems (Figure 3B). Overall, the SOC level was generally poor according to ARPAV (2007). In 2008, SOC content in OF was higher (26.6% on average) compared to CF; nine years later, the difference was not significant due to the SOC decrease in OF from 9.0 g kg^{-1} in 2008 to 8.3 g kg^{-1} in 2017 (Figure 3B). In contrast to our findings, Schrama *et al*. (2018) observed a higher percentage of SOM in OF fertilized with manure than in CF fertilized with slurry or mineral with a similar fertilization strategy and period as our study. The different findings may be due to different soil textures, climatic conditions, cultivated crops, and yield gaps between the studies. Although organic farming is considered to improve SOC concentrations (Tuomisto *et al*., 2012), the increase in SOC should be specifically evaluated in relation to the adopted agricultural practices; namely, the use of organic amendments, conservation tillage, and cover crops (Leifeld and Fuhrer, 2010; Crystal-Ornelas *et al*., 2021). In our organically managed site, of these three practices, only organic amendments were applied. The SOC concentration trend observed in this study in the OF soil can be ascribed to: i) the frequency of tillage in OF was higher than that in CF, to mechanically manage weeds; ii) the crop yield was, on average, 32% lower in OF than in CF (details in Dal Ferro *et al*., 2017) with consequent lower residues. The stable SOC concentration in CF can be explained considering that slurry application provided a lower cumulative C input in CF than in OF. However, the greater amount and ready availability of mineral fertilizers permitted higher crop yields in CF (Dal Ferro *et al*., 2017), so a higher amount of organic matter returned to the soil as crop residues. In addition, fewer tillage operations in CF may have contributed to the preservation of C stock. While SOC content in CF remained fairly stable between 2008 and 2017, the trend observed in the OF might suggest the risk of a future SOC concentration decrease despite inputs from organic amendments. This is in line with the work of Berti *et al*. (2016) in the same location, who observed long-term declining trends of SOC content in the plowing layer, regardless of fertilization and residue management; however, the use of farmyard manure slowed the decline. SOC accumulation in the topsoil occurred at approximately 7.5 g kg^{-1} as observed in our CF system. Our findings confirmed the results of the modelling approach of Longo *et al*. (2021) that did not find clear evidence of a generalized topsoil SOC increase under organic farming; hypothesizing that organic farming can suffer from low residue and root carbon inputs, which may offset the positive effect of adding external organic material.

TKN did not significantly change over time in either farming system. However, it was higher (22.2%) in OF than in CF (Figure 3C) in both sampling years. TKN remained consistently higher in OF over time, probably because of the notable amount of manure applied (Table 2). The latter was characterized by a higher content of organic N (about 2.1 times) compared to the slurry that was used in CF in addition to the mineral N.

The soil C/N ratio was not significantly different between OF and CF within the same sampling time, but on average significantly decreased from 2007 (8.34) to 2017 (7.95). A C/N ratio lower than 10 highlights high mineralization activity (Riffaldi *et al*., 1996), which may explain the lack of organic matter accumulation.

Available P increased over time, being on average 50.3% higher in 2017 than in 2008 (Figure 3D). The management system did not significantly influence soil PO_4-P content despite the CF fertilization strategy applying more P (on average 79.4 and 102.6 Kg P_2O_5 ha^{-1} year^{-1} in OF and CF, respectively). These results are in line with those obtained by van Diepeningen *et al*. (2006), who did not observe any difference in phosphate and total phosphorus between soils under different management conditions. This may indicate that differences in the systems could not be assessed with sufficient confidence, or that the two types of management had no real impact on PO_4-P content. Therefore, no conclusions should be drawn on the difference in available P between the two farms. However, the build-up of PO_4-P over time indicates that a surplus of P is achieved through fertilization, with respect to crop requirements.

A summary of the results of the Wald test ANOVA for each chemical variable is provided in Table 4, to complement the information provided in this section.

Effects of texture on soil chemical properties

The relationship between each chemical property and clay was investigated to obtain a more reliable quantification of the effects of the farming system and year. Clay was chosen as the only textural property to be used as a covariate since: i) texture, in general, does not change over time; ii) textural properties are interrelated, so only one of them can be appropriately used as a covariate; and iii) the relationship between clay and SOM has long been known (Burke *et al*., 1989), and a relationship between N and SOC (and thus clay) was observed in a long-term trial close to our site (Nardi *et al*., 2004).

Despite all chemical properties being investigated and accounting for the spatiotemporal structure of the experiment, the only chemical variables with significant relationships with clay were SOC and N. The relationships with other chemical variables were not significant and were therefore excluded from the models. Figures 4 and 5 show the regressions between SOC and clay and

Table 4. Results of the Wald-test ANOVA on the final models (only the predictors included in the final model are presented).

Outcome	Predictors	Chisq	Df	P-value
SOC (g kg^{-1})	Clay (%)	4.4028	1	0.036*
	Farm	14.5528	1	0.000***
	Year	0.9681	1	0.325
	Farm:Year	7.7762	1	0.005**
TKN (g kg^{-1})	Clay (%)	7.3618	1	0.007**
	Farm	64.1110	1	0.000***
	Year	2.7922	1	0.095
pH	Farm	9.4215	1	0.002**
	Year	4.1445	1	0.042*
	Farm:Year	53.0485	1	0.000***
PO_4-P (mg kg^{-1})	year	10.3200	1	0.001**

SOC, soil organic carbon; TKN, total Kjeldahl nitrogen content; Chisq, Wald chi-square; Df, degrees of freedom; Farm:Year, interaction; *P<0.05; **P<0.01; ***P<0.001.

TKN and clay, respectively. Regardless of farm management and sampling year, SOC and TKN increased at a rate of 0.0536 and 0.0054 g kg^{-1} per percentage point of clay, respectively (slope of the regression). This confirmed our initial hypothesis regarding the link between SOM and clay and allowed us to obtain unbiased estimates of the effects of farming system and year on the investigated chemical properties.

Dexter *et al*. (2008) and Johannes *et al*. (2017) proposed the SOC:clay ratio as a relevant criterion for evaluating the soil structure quality. This criterion allows for the evaluation of the evolution of soil quality over time in different management systems. A 1:8 ratio indicates a good structure quality, a 1:10 ratio indicates a reasonable goal for farmers, and a 1:13 ratio indicates a degraded structure that needs improvement (Johannes *et al*., 2017). Ratios above this value have a 'bad' soil structure quality. In our study, the SOC:clay ratio increased from 1:17.2 to 1:18.2 and from 1:18.2 to 1:20.1 in CF and OF, respectively, indicating a decrease in soil quality over time. The decrease was more marked in OF, suggesting that the negative effect of soil tillage offsets the positive effect of higher C supply.

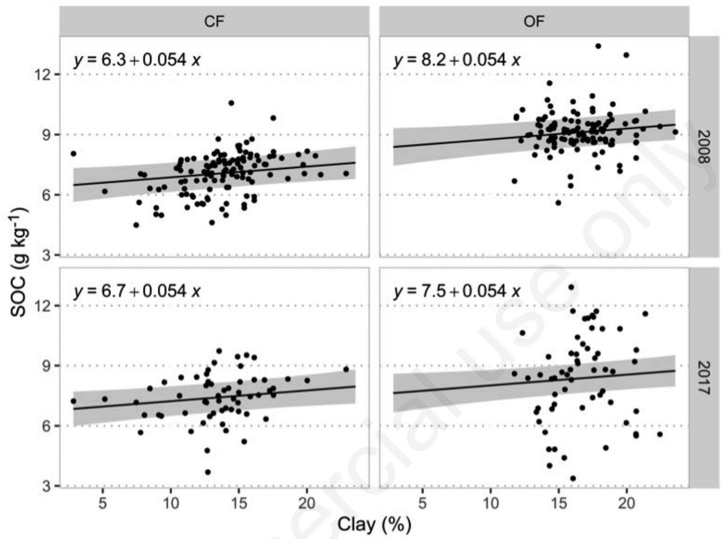

Figure 4. Average response of soil organic carbon (SOC) (g kg^{-1}) to changes of clay content (%). Estimated regression line (thick) and 95% confidence interval (dotted lines) are reported. Regression between SOC and clay was significant with P=0.036. OF, organic farm; CF, conventional farm.

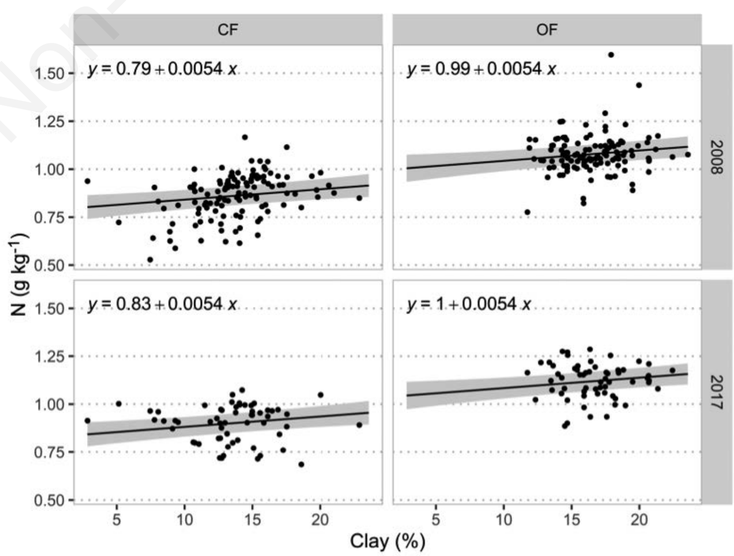

Figure 5. Average response of total Kjeldahl nitrogen (TKN) (g kg^{-1}) to changes in clay content (%). Regression line (thick) and 95% confidence interval (dotted lines) are reported. Regression between N and clay was significant with P=0.007. OF, organic farm; CF, conventional farm.

Conclusions

Farm history, management, and pedoclimatic conditions contribute to soil fertility. In our study, despite the experimental sites being close to each other, the SOC, TKN, and pH soil properties revealed notable differences between the two management systems (organic and conventional). TKN was affected by the farm management (higher in the OF than CF), while the pH was influenced by the interaction between the farm management and time (decreased in OF and increased in CF). The SOC content in CF remained fairly stable over the study period, whereas it showed a slightly decreasing trend in OF despite inputs from organic amendments. This suggests that agroecosystem organic management does not necessarily have positive effects by increasing SOC, and that if well-managed, conventional agroecosystems do not necessarily have negative effects on soil fertility.

References

Alvarez R, 2021. Comparing productivity of organic and conventional farming systems: a quantitative review. Archiv. Agron. Soil Sci. [Epub ahead of print].

ARPAV, Veneto Agricoltura, 2007. L'interpretazione delle analisi del terreno, strumento per la sostenibilità ambientale. Available from: https://www.arpa.veneto.it/arpavinforma/ pubblicazioni/linterpretazione-delle-analisi-del-terreno/at_download/file

Beck HE, Zimmermann NE, McVicar TR, Vergopolan N, Berg A, Wood EF, 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Sci. Data 5:1-12.

Berti A, Morari F, Dal Ferro N, Simonetti G, Polese R, 2016. Organic input quality is more important than its quantity: C turnover coefficients in different cropping systems. Eur. J. Agron. 77:138-45.

Berti A, Tardivo G, Chiaudani A, Rech F, Borin M, 2014. Assessing reference evapotranspiration by the Hargreaves method in north-eastern Italy. Agric. Water Manage. 140:20-5.

Brevik EC, Slaughter L, Singh BR, Steffan JJ, Collier D, Barnhart P, Pereira P, 2020. Soil and human health: current status and future needs. Air Soil Water Res. 13:1-23.

Burke IC, Yonker CM, Parton WJ, Cole CV, Flach K, Schimel DS, 1989. Texture, climate, and cultivation effects on soil organic matter content in US grassland soils. Soil Sci. Soc. Am. J. 53:800-5.

Cano A, Núñez A, Acosta-Martinez V, Schipanski M, Ghimire R, Rice C, West C, 2018. Current knowledge and future research directions to link soil health and water conservation in the Ogallala Aquifer region. Geoderma 328:109-18.

Cavalcante DM, de Silva APF, de Almeida BG, Freire FJ, dos Santos Silva TH, Cavalcante FMS, 2021. Physical soil quality indicators for environmental assessment and agricultural potential of Oxisols under different land uses in the Araripe Plateau, Brazil. Soil Till. Res. 209:104951.

Clark MS, Horwat WR, Shennan C, Scow KM, 1998. Changes in soil chemical properties resulting from organic and low□input farming practices. Agron. J. 90:662-71.

Crawley MJ, 2007. Mixed-effects models. The R Book, 627-666. Available from: https://www.cs.upc.edu/~robert/teaching/ estadistica/TheRBook.pdf

Crystal-Ornelas R, Thapa R, Tully KL, 2021. Soil organic carbon is affected by organic amendments, conservation tillage, and cover cropping in organic farming systems: A meta-analysis. Agric. Ecosyst. Environ. 312:107356.

Dal Ferro N, Zanin G, Borin M, 2017. Crop yield and energy use in organic and conventional farming: A case study in north-east Italy. Eur. J. Agron. 86:37-47.

De Valença AW, Vanek SJ, Meza K, Ccanto R, Olivera E, Scurrah M, Lantinga EA, Fonte SJ, 2017. Land use as a driver of soil fertility and biodiversity across an agricultural landscape in the Central Peruvian Andes. Ecol. Appl. 27:1138-54.

Dexter AR, Richard G, Arrouays D, Czyż EA, Jolivet C, Duval O, 2008. Complexed organic matter controls soil physical properties. Geoderma 144:620-7.

Dionisi CP, Mignone RA, Rubenacker AI, Pfaffen V, Bachmeier O, Campitelli PA, Juarez AV, 2020. Monitoring of physicochemical parameters of soils after applying pig slurry. Analysis of its application in short and long periods in the province of Córdoba, Argentina. Microchem. J. 159:105545.

Doran JW, Parkin TB, 1997. Quantitative indicators of soil quality: a minimum data set. Methods Assess. Soil Qual. 49:25-37.

Drinkwater LE, Letourneau DK, Workneh FAHC, Van Bruggen AHC, Shennan C, 1995. Fundamental differences between conventional and organic tomato agroecosystems in California. Ecol. Appl. 5:1098-112.

Dubois O, 2011. The state of the world's land and water resources for food and agriculture: managing systems at risk. Earthscan. FAO, Rome, Italy.

Eswaran H, Lal R, Reich PF, 2019. Land degradation: an overview. Resp. Land Degrad. 20-35.

Fiorini A, Boselli R, Maris SC, Santelli S, Perego A, Acutis M, Brenna S, Tabaglio V, 2020. Soil type and cropping system as drivers of soil quality indicators response to no-till: a 7-year field study. Appl. Soil Ecol. 155:103646.

Fließbach A, Oberholzer HR, Gunst L, Mäder P, 2007. Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. Agric. Ecosyst. Environ. 118:273-84.

Gosling P, Shepherd M, 2005. Long-term changes in soil fertility in organic arable farming systems in England, with particular reference to phosphorus and potassium. Agric. Ecosyst. Environ. 105:425-32.

Grilli E, Carvalho SC, Chiti T, Coppola E, D'Ascoli R, La Mantia T, Marzaioli R, Mastrocicco M, Pulido F, Rutigliano FA, Quatrini P, Castaldi S, 2021. Critical range of soil organic carbon in southern Europe lands under desertification risk. J. Environ. Manage. 287:112285.

Hartemink AE, 2006. Assessing soil fertility decline in the tropics using soil chemical data. Adv. Agron. 89:179-225.

Hartig F, 2021. DHARMa: Residual diagnostics for hierarchical (multi-level/mixed) regression models. R package version 0.4.0. Available from: https://CRAN.R-project.org/ package=DHARMa

Johannes A, Matter A, Schulin R, Weisskopf P, Baveye PC, Boivin P, 2017. Optimal organic carbon values for soil structure quality of arable soils. Does clay content matter?. Geoderma 302:14-21.

Kaiser K, Guggenberger G, 2000. The role of DOM sorption to mineral surfaces in the preservation of organic matter in soils. Organ. Geochem. 31:711-25.

Kiboi MN, Ngetich FK, Muriuki A, Adamtey N, Mugendi D, 2020. The response of soil physicochemical properties to tillage and soil fertility resources in Central Highlands of Kenya. Ital. J. Agron. 15:71-87.

Kurki P, Nurmi E, Haikarainen I, Savikurki R, Kaseva J, Hakala K, Valkama E, 2021. Crushed bark as a novel soil conditioner for organic plant production. Ital. J. Agron. 16:1781.

Leifeld J, Fuhrer J, 2010. Organic farming and soil carbon sequestration: what do we really know about the benefits?. Ambio 39:585-99.

Lenth RV, 2021. Emmeans: estimated marginal means, aka least-squares means. R package version 1.6.1. Available from: https://CRAN.R-project.org/package=emmeans

Longo M, Dal Ferro N, Lazzaro B, Morari F, 2021. Trade-offs among ecosystem services advance the case for improved spatial targeting of agri-environmental measures. J. Environ. Manage. 285:112131.

McLauchlan K, 2006. The nature and longevity of agricultural impacts on soil carbon and nutrients: a review. Ecosyst. 9:1364-82.

Montanarella L, 2020. Soils and the European Green Deal. Ital. J. Agron. 15:262-6.

Montanarella L, Badraoui M, Chude V, Costa IDSB, Mamo T, Yemefack M, Singh Aulakh M, Yagi K, Young Hong S, Vijarnsorn P, Zhang GL, Arrouays D, Black H, Krasilnikov P, Sobocka J, Alegre J, Henriquez C, Mendonça-Santos M, Taboada M, Espinosa-Victoria D., AlShankiti A, AlaviPanah SK, El-Sheikh EAEM, Hempel J, Pennock D, Camps Arbestain M, McKenzie N, 2015. Status of the world's soil resources: main report. Embrapa Solos-Livro científico (ALICE). FAO, Rome, Italy, pp. 1-608.

Moran-Salazar RG, Sanchez-Lizarraga AL, Rodriguez-Campos J, Davila-Vazquez G, Marino-Marmolejo EN, Dendooven L, Contreras-Ramos SM, 2016. Utilization of vinasses as soil amendment: consequences and perspectives. SpringerPlus 5:1-11.

Nardi S, Morari F, Berti A, Tosoni M, Giardini L, 2004. Soil organic matter properties after 40 years of different use of organic and mineral fertilisers. Eur. J. Agron. 21:357-67.

Onofri A, Seddaiu G, Piepho HP, 2016. Long-term experiments with cropping systems: case studies on data analysis. Eur. J. Agron. 77:223-35.

R Core Team, 2021. R: A Language and Environment for Statistical Computing; R Foundation for Statistical Computing, Vienna, Austria. Available from: https://www.R-project.org/

Reeve JR, Hoagland LA, Villalba JJ, Carr PM, Atucha A, Cambardella C, Delate K, 2016. Organic farming, soil health, and food quality: considering possible links. Adv. Agron. 137:319-67.

Riffaldi R, Saviozzi A, Levi-Minzi R, 1996. Carbon mineralization kinetics as influenced by soil properties. Biol. Fertil. Soils 22:293-8.

Schrama M, De Haan JJ, Kroonen M, Verstegen H, Van der Putten WH, 2018. Crop yield gap and stability in organic and conventional farming systems. Agric. Ecosyst. Environ. 256:123-30.

Singh B, 2018. Are nitrogen fertilizers deleterious to soil health?. Agronomy 8:48.

Sofo A, Zanella A, Ponge JF, 2022. Soil quality and fertility in sustainable agriculture, with a contribution to the biological classification of agricultural soils. Soil Use Manage. 38:1085-112.

Suja G, Byju G, Jyothi AN, Veena SS, Sreekumar J, 2017. Yield, quality and soil health under organic vs conventional farming in taro. Sci. Hortic. 218:334-43.

Tuomisto HL, Hodge ID, Riordan P, Macdonald DW, 2012. Does organic farming reduce environmental impacts? - A meta-analysis of European research. J. Environ. Manage. 112:309-20.

Van Diepeningen AD, de Vos OJ, Korthals GW, van Bruggen AH, 2006. Effects of organic versus conventional management on chemical and biological parameters in agricultural soils. Appl. Soil Ecol. 31:120-35.

Watson CA, Atkinson D, Gosling P, Jackson LR, Rayns FW, 2002. Managing soil fertility in organic farming systems. Soil Use Manage. 18:239-47.

Willer H, Sahota A, 2020. The world of organic agriculture, statistics and emerging trends 2020 at BIOFACH 2020. Available from: https://orgprints.org/id/eprint/37557/1/willer-et-al-2020-global-stats.pdf

Yilmaz E, Alagöz Z, 2010. Effects of short-term amendments of farmyard manure on some soil properties in the Mediterranean region - Turkey. J. Food Agric. Environ. 8:859-62.

Zinn YL, Lal R, Bigham JM, Resck DV, 2007. Edaphic controls on soil organic carbon retention in the Brazilian Cerrado: texture and mineralogy. Soil Sci. Soc. Am. J. 71:1204-14.