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Low efficacy of different crop residue management on C and N stocks after five decades

I. Piccoli *, R. Polese, A. Berti

Department of Agronomy, Food, Natural Resources, Animals and Environment, University of Padova, Viale dell'Università 16, Legnaro 35020, Italy

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ABSTRACT

Increasing the soil organic carbon (SOC) content is gaining growing attention nowadays due to its double function of restoring soil fertility and mitigating climate change. This study aims to investigate the effect of different residue management including residue removal, residue incorporation, and residue incorporation + 1 t ha^{-1} poultry manure, on SOC, soil inorganic carbon (SIC), total soil carbon (TSC), total Kjeldahl nitrogen (TN) and C:N ratio on a long-term experiment located in North-East Italy. After 55 years of residue retention, SOC content increased by ~12 % in the tilled topsoil and 6 % in the subsoil. Among the 0–60 cm soil profile, this corresponded to a SOC storage of ~6 t ha^{-1} that was achieved in response to ~127 t ha^{-1} residue-derived C input. Therefore, assuming that C sequestration was linear during the experimentation, an average annual conversion rate from residue-derived C to SOC can be estimated as 4.7 % which is comparable to what is usually reported in the literature. The addition of poultry manure only marginally affected the SOC stock while increasing the 0–30 cm TN stock of 0.5 t TN ha^{-1}, demonstrating how it acts more as a mineral source of N rather than affecting the soil organic matter (OM) dynamics. Any significant effect of treatments was instead found on SIC, TSC, and C:N. Crop residue incorporation increased the SOC stock, but its low conversion efficiency might suggest a different use (e.g., bioenergy production). Despite not improving the OM dynamics, poultry manure can be used as an alternative to mineral fertilizers, reducing fossil fuel consumption and giving new insight into the circular economy.

1. Introduction

Increasing soil organic carbon (SOC) is gaining growing attention nowadays due to its double function of restoring soil fertility (Tiessen et al., 1994) and mitigating climate change (Chabbi et al., 2017). The "4 per 1000" (URL: http://4p1000.org/understand) (Minasny et al., 2017) COP21 initiative further highlighted how also agricultural soils can play a key role in achieving food security (Poulton et al., 2018; Rumpel et al., 2018; Soussana et al., 2019).

Recently, Minasny et al. (2017) reviewed soil management practices to investigate their capacity to maintain and/or increase soil SOC levels within the "4 per 1000" concept. Among these practices, apart from practices involving a land-use change (e.g., from arable to pastures or perennial grasses), the authors identified the change in soil tillage operations toward reduced or no-tillage and the use of organic amendments and crop residue incorporation (Minasny et al., 2017). In the Veneto region (NE Italy) agroecosystem, the animal husbandry intensification made available liquid slurry, as a main animal waste, being affected by difficulties in its transportation over long distances while farmyard manure and compost are nowadays poorly available for extensive application. In this context, together with crop residue, poultry manure might represent a valid alternative as organic amendment, being organic C- and nutrients-rich. The combination of crop residues with poultry manure and mineral fertilizers was previously suggested as a strategy to increase SOC stock (Amanullah et al., 2007; Poblete-Grant et al., 2020) and gain the "4 per 1000" objective where other types of amendments are not readily available.

This study aims to examine the impact of 55 years of various crop residue management practices, either alone or in conjunction with the addition of poultry manure, on various forms of soil carbon (organic, inorganic, and total) as well as total Kjeldal nitrogen content, with consideration given to both the topsoil (0–30 cm) and the subsoil (30–60 cm).

The starting hypotheses are that i) crop residue incorporation is expected to increase the SOC stock (Lehtinen et al., 2014) and, ii) this effect will be further accentuated by poultry manure addition (Maillard

* Corresponding author.
E-mail address: ilaria.piccoli@unipd.it (I. Piccoli).

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and Angers, 2014) which is also expected to increase the soil nitrogen stock (Watts et al., 2010).

2. Materials and methods

2.1. Experimental site and design

The long-term trial is located at the University of Padova experimental farm (Veneto Region, NE Italy 45°21′N; 11°58′E; 6 m a.s.l.). The local climate is temperate sub-humid (Cfa according to Peel et al., 2007), with 850 mm of annual rainfall and temperatures rising from January (minimum average: −1.5°C) to July (maximum average: 27.2°C). In the median year, rainfall is highest in June (100 mm) and October (90 mm) and lowest in winter (50–60 mm). Reference evapotranspiration (ET_0) is 945 mm with a peak in July (5 mm d^{-1}) and it exceeds rainfall from April to September. The site has a shallow water table ranging from about 0.5–1.5 m in late winter–early spring to 1–2 m in the summer. The soil is a Fluvi-Calcaric Cambisol (WRB, 2014) with a silt loam texture. At the start of the experiment, the carbonate content was measured as 33.1 %, with a soil pH of 7.8, bulk density of 1.44 g cm^{-3}, organic carbon content of 1.04 %, and a 8.3 C:N ratio in the 0–30 cm soil layer.

Since 1966 the experimental design is a split plot with four replications (4 blocks) on 60 plots (5.4 ×6.4 m^2) derived from the factorial combination between 3 levels of crop residue management and 5 levels of N fertilization. For each block, the splitting factor consists of three different levels of crop residue management: residue removal "RR", previous crop residue incorporation "RI" and residue incorporation with 1 t ha^{-1} of dried poultry manure "RI+PM". The N fertilization levels (0, 60, 120, 180 and 240 kg N ha^{-1}) are then randomized within the main plot. Until 1981, mineral N was applied as ammonium-nitrate, afterwards substituted by urea. Mineral N is supplied in two top-dressing applications. In spring and summer crops, N distribution is followed by 7-cm inter-row cultivation. All plots are tilled with conventional methods, namely autumn ploughing (35 cm-depth) followed by seedbed preparation with rotary harrowing (15 cm-depth) at different times, according to the crop requirements and receive the same amounts of P (65.5 kg ha^{-1} y^{-1}) and K (124.5 kg ha^{-1} y^{-1}) at sowing by mineral fertilisers. In RI and RI+PM the crop residues are chopped during the harvest and buried with the ploughing. In RI+PM poultry manure is simultaneously incorporated together with residue providing about 40 kg N ha^{-1} and 410 kg OC ha^{-1}.

The trial was conducted with maize (*Zea mays* L.) in monoculture until 1984. Thereafter, a variable rotation scheme was used mainly based on maize, sugar beet (*Beta vulgaris* L.), winter wheat (*Triticum aestivum* L.), potato (*Solanum tuberosum* L.), soybean (*Glycine max* (L.) Merr.), and tomato (*Solanum lycopersicum* L.). For a single year sorghum (*Sorghum vulgare* Pers.) and sunflower (*Helianthus annuus* L.) were also grown (Fig. 1).

2.2. Soil sampling, preparation, and laboratory analysis

Soil sampling was performed in September 2020, a few months after the winter wheat harvesting.

Disturbed soil samples of the topsoil (0–30 cm) and subsoil (30–60 cm) were taken from five different points of each plot and mixed

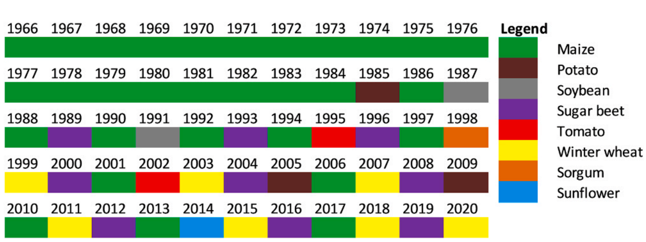

Fig. 1. Sequence of crops at the long-term experiment.

to obtain one sample of about three kg. In total 60 disturbed soil samples were air-dried, crushed by rolling pin to break up clods, sieved through a 2-mm sieve and stored at low humidity. For SOC analysis a sub-sample was ground in a mortar and pestle to pass a 0.5-mm sieve. Organic carbon was determined with high-temperature catalytic combustion (SKALAR Primacs ATC100-E, SKALAR Analytical B.V., Breda, The Netherlands) that coupled high-temperature combustion with non-dispersive infrared detection (NDIR) to determine all the C forms, according to DIN19539. In brief, samples are positioned at different heights in the combustion furnace where each height has a different temperature. The first peak, measured at 400 °C, is the SOC value, the second peak at 600 °C is the elemental carbon (EC) value and the last value at 900 °C is for soil inorganic carbon (SIC). EC was not detected in the present soil, therefore the total soil carbon was calculated as the sum of SOC and SIC. The total nitrogen was analysed by the Kjeldahl method (TN). The C:N ratio was calculated as the ratio between SOC and TN concentration.

60 undisturbed soil cores, 7 cm diameter and 90 cm height, were collected in the 0–60 cm soil profile of each plot by using a hydraulic sampler. Soil cores were then cut every 10 cm into 6 distinct layers (0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm and 50–60 cm) and stored at 4°C until analyses. Afterwards, the 360 soil cores (3 residue management x 5 N levels x 4 block x 6 soil layers) were extracted from the cylinders, gently broken into small aggregates and oven-dried at 105°C until constant weight to calculate the dry weight. For each sample, the bulk density was calculated as the ratio between dry weight and internal cylinder volume.

The SOC, SIC, TSC and TN stocks were calculated according to the equivalent soil mass (ESM) concept (VandenBygaart and Angers, 2006) by using the equation already reported in Piccoli et al. (2016) to account for the differences in bulk density (Post et al., 2001). The bulk density value used for SOC stock calculation in the 0–30 and 30–60 cm soil profiles was derived by averaging the bulk density measured among these layers.

The 0–30 cm SOC stock obtained in 2020 was then compared in the discussion section with the pre-existent soil data series (1966, 1982, 1986, 1993, 115 2006) already published in Lugato et al. (2006) and Poeplau et al. (2017) in order to evaluate the SOC evolution at this site.

2.3. Residue-derived C input

The residue-derived soil C input was estimated as 45 % of dry crop residue biomass weight after oven-dried at 65 °C until constant weight. The residue biomass dry weight of each plot was measured every year at the end of each growing season (1966–2020).

2.4. Statistical analysis

A two-way factorial ANOVA for split-plot design was applied to BD, SOC, SIC, TSC and TN concentration, C:N ratio and SOC, SIC, TSC and TN stocks considering the block as replication, residue management as the main-plot factor and N dose as the sub-plot factor.

The post-hoc test was performed with the Tukey method for $p<0.05$. Before statistical analysis, the assumptions of normality and homoscedasticity of the residuals were assessed by visual inspection of Q-Q plots and by plotting the normalized residuals against the fitted values, respectively.

The statistical data analysis was performed using DSAASTAT Excel add-in (Onofri and Pannacci, 2014), version 1.154.

3. Results

3.1. Soil bulk density

Soil BD was not affected by treatment, N dose or their interaction except from the 10–20 cm soil layer (Table 1). Indeed, in the latter, a

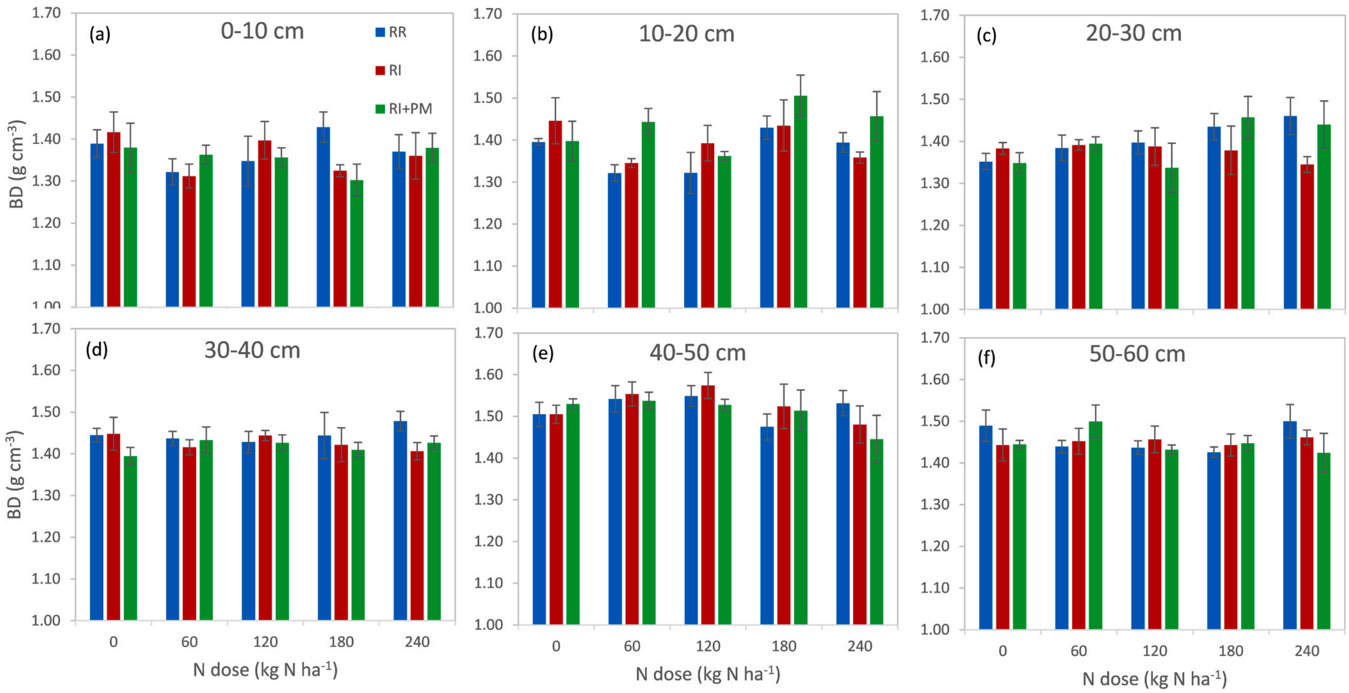

Fig. 2. Mean bulk density as affected by crop residue management and N application dose. Bars represent the standard error.

Table 1
P-value of two-ways ANOVA testing the effect of residue management, N dose and their interaction on bulk density (BD) at different soil layers and on residue-derived C input. Significant values were underlined.

	Bulk density						Residue-derived C input
	0–10 cm	10–20 cm	20–30 cm	30–40 cm	40–50 cm	50–60 cm	
Residue management	0.92	0.40	0.60	0.42	0.66	0.88	<0.01
N dose	0.30	<0.01	0.20	0.98	0.13	0.70	<0.01
Residue management x N dose	0.32	0.19	0.39	0.73	0.73	0.41	<0.01

significant N dose effect was revealed with lower BD in 60 and 120 kg N ha^{-1} (1.6 g cm^{-3}, on average) compared with 180 kg N ha^{-1} (1.46 g cm^{-3}), while 0 and 240 kg N ha^{-1} showed intermediate value.

3.2. Crop residue-derived C input

The C input from crop residue ranged between 0.09 and 5.024 t C ha^{-1}, being firstly dependent upon the crop type. The ANOVA test showed significant residue management x N dose interaction (Table 1). Without N input (i.e., 0 kg N ha^{-1}) the treatment ranked as follows: RI+PM (1.98 t C ha^{-1}) > RI (1.78 t C ha^{-1}) > RR (0 t C ha^{-1}) while in all the other N doses (60, 120, 180 and 240 kg N ha^{-1}) any difference was detected between RI+PM and RI and the averages between the two treatments were 2.22 t C ha^{-1}, 2.47 t C ha^{-1}, 2.55 t C ha^{-1}, 2.61 t C ha^{-1} for 60, 120, 180 and 240 kg N ha^{-1}, respectively.

During the 55 years of experiment, the different residue managements received a cumulative C input from crop residue of 129.1, 124.3 and 0 t C ha^{-1} for RI+PM, RI and RR, respectively.

3.3. Soil organic carbon, soil inorganic carbon and soil total carbon concentrations

The 0–30 cm SOC concentration was affected by both residue management and N dose (Table 2) with greater values where residues are incorporated (i.e., RI and RI+PM) compared to RR and with 120 kg N ha^{-1} compared to 0 kg N ha^{-1} (Fig. 3-a). The 60, 180 and 240 kg N ha^{-1} doses observed an intermediate value of 0.90 g C 100 g^{-1}, on average. The SOC concentration in the 30–60 cm layer was significantly affected only by N dose but the Tukey test was unable to reveal differences between N doses.

The SIC was unaffected by both residue management and N dose at both layers (Table 2) with means of 3.28 (0–30 cm) and 3.27 g C 100 g^{-1} (30–60 cm).

Similarly, the 0–30 cm STC averaged 4.18 g C 100 g^{-1} without any significant residue management or N dose effect (Table 2). In the 30–60 cm layer N dose affected the STC with a p=0.06 showing a greater value at 180 compared to 60 kg N ha^{-1} (4.19 vs 4.14 g C 100 g^{-1}). For

Table 2
P-value of two-ways ANOVA testing the effect of residue management, N dose and their interaction on soil organic carbon (SOC), soil inorganic carbon (SIC), total soil carbon (TSC) and total nitrogen concentration (TN) and C:N ratio at different soil layers. Underlined values were considered as significant.

	SOC		SIC		TSC		TN		C:N	
	0–30 cm	30–60 cm	0–30 cm	30–60 cm	0–30 cm	30–60 cm	0–30 cm	30–60 cm	0–30 cm	30–60 cm
Residue management	<0.01	0.24	0.08	0.38	0.25	0.53	0.03	0.33	1.00	0.54
N dose	<0.01	0.05	0.87	0.22	0.26	0.06	0.32	0.06	0.94	0.86
Residue management x N dose	0.82	0.21	0.27	0.81	0.50	0.73	0.51	0.18	0.56	0.03

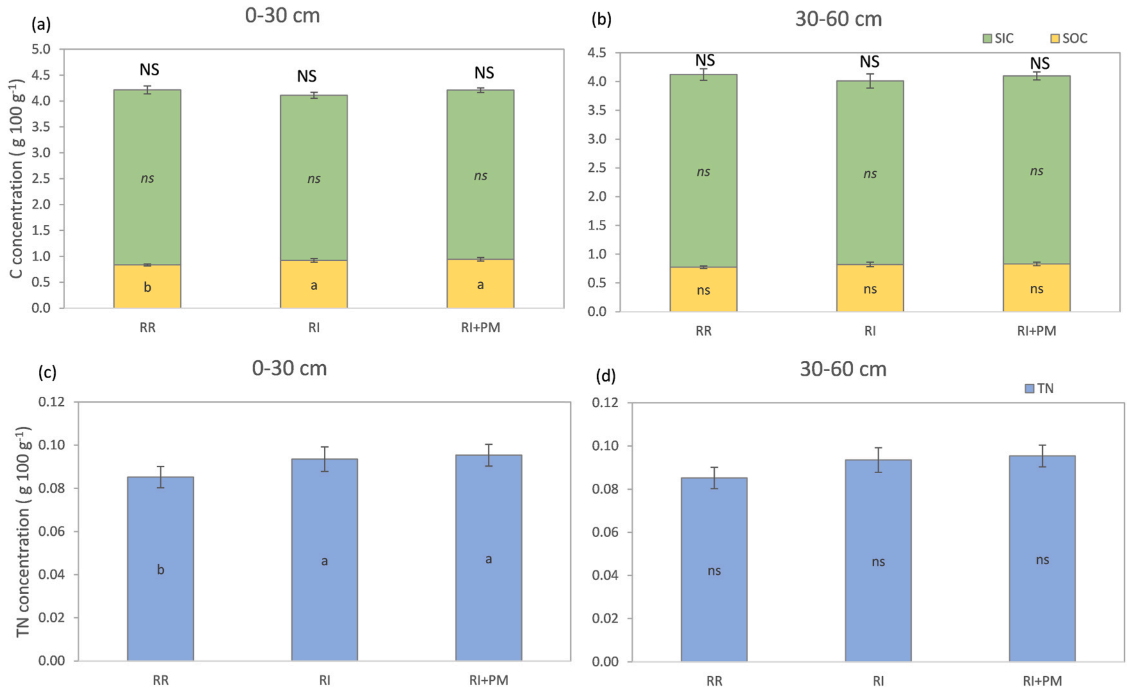

Fig. 3. SOC (a,b) and TN concentration (c,d) at the 0–30 (a,c) and 30–60 cm (b,d) soil layer. Different letters represent a significant effect of residue management at p ≤0.05.

more information, please see supplementary material Table S1.

3.4. Total Kjeldahl nitrogen concentration and C:N ratio

The residue management significantly affected the 0–30 cm TN (Table 2) with greater content where residues are incorporated (i.e., RI and RI+PM) than RR (Figure 3 -c). The 30-60 cm TN was unaffected by treatments, being 0.083 g N 100 g^{-1} on average.

The C:N ratio was in the 8.7–13.2 and 8.5–12.2 ranges respectively for the 0–30 and 30–60 cm. Its value averaged 9.9 for 0–30 cm and 9.8 for 30–60 cm. The statistical analysis evidenced only a significant effect of the Treatment x N dose interaction in the 30–60 cm (Table 2) but the post-hoc test was not able to reveal a difference between the compared means. For more information, please see supplementary material Table S1.

3.5. Carbon and nitrogen stock

The SOC stock was affected by residue management at 0–30 cm and 0–60 cm soil profiles (Table 3), following the same trend seen previously for concentration, i.e., with greater values where residues are incorporated compared with RR (Fig. 4-a,b). The N dose significantly affected the SOC stock at all the three studied soil profiles (Table 3) but the Tukey test showed significant differences only at 0–30 cm where 120 kg N ha^{-1} had greater SOC stock compared with 0 kg N ha^{-1}. In the 30–60 cm soil layer, the SOC stock averaged 35.6 t C ha^{-1}.

The SIC stock was unaffected by any tested factor (Table 3, Fig. 4-a,b) averaging 136.3 and 143.9 t C ha^{-1} at 0–30 and 30–60 cm. Within the entire 0–60 cm layer the mean SIC stock was calculated as 280.2 t C ha^{-1}.

The TSC, calculated, as the sum of SOC and SIC, amounted to 158.7, 171.2 and 329.9 t C ha^{-1} in the 0–30, 30–60 and 0–60 cm layers, respectively. Despite the factorial ANOVA showed a significant effect of N dose at both 30–60 and 0–60 cm layer, the posthoc test revealed differences between 180 and 60 kg N ha^{-1} only at 30–60 cm (175.9 vs 166.9 t C ha^{-1}).

The TN stock was affected by residue management only at 0–30 cm layer with significantly greater stock in RI+PM compared to RR while RI amounted to intermediate value (Fig. 4-c). At 30–60 and 0–60 cm soil profile a significant N dose was evidenced by factorial ANOVA (Table 3) but the Tukey test was not able to find any differences between the treatments. The average TN stock was 3.7 t N ha^{-1} in the 30–60 cm layer and 7.0 t N ha^{-1} in the 0–60 cm soil profile. For more information, please see supplementary material Table S2.

4. Discussion

4.1. Effects on soil bulk density

The BD is one of the main soil indicators used for soil structure in cultivated soils (Blake and Hartge, 1986). Indeed, too low BDs might lead to poor seed germination due to insufficient seed-soil contact. On the contrary, too dense BDs might result in both greater soil strength and reduced gas exchanges with the atmosphere that, in turn, might impair plant rooting and potentially increase greenhouse gas emissions (Bogunović et al., 2014). Recently, Schjønning et al. (2023) found

Table 3
P-value of two-ways ANOVA testing the effect of residue management, N dose and their interaction on soil organic carbon (SOC), soil inorganic carbon (SIC), total soil carbon (TSC) and total nitrogen (TN) stocks at different soil layers. Underlined values were considered as significant.

	SOC stock			SIC stock			STC stock			TN stock		
	0–30 cm	30–60 cm	0–60 cm	0–30 cm	30–60 cm	0–60 cm	0–30 cm	30–60 cm	0–60 cm	0–30 cm	30–60 cm	0–60 cm
Residue management	0.01	0.17	0.04	0.08	0.33	0.16	0.25	0.48	0.30	0.03	0.28	0.10
N dose	<0.01	0.02	<0.01	0.87	0.20	0.27	0.26	0.05	0.05	0.32	0.04	0.06
Treatment x N dose	0.82	0.25	0.41	0.27	0.80	0.68	0.50	0.70	0.56	0.51	0.17	0.28

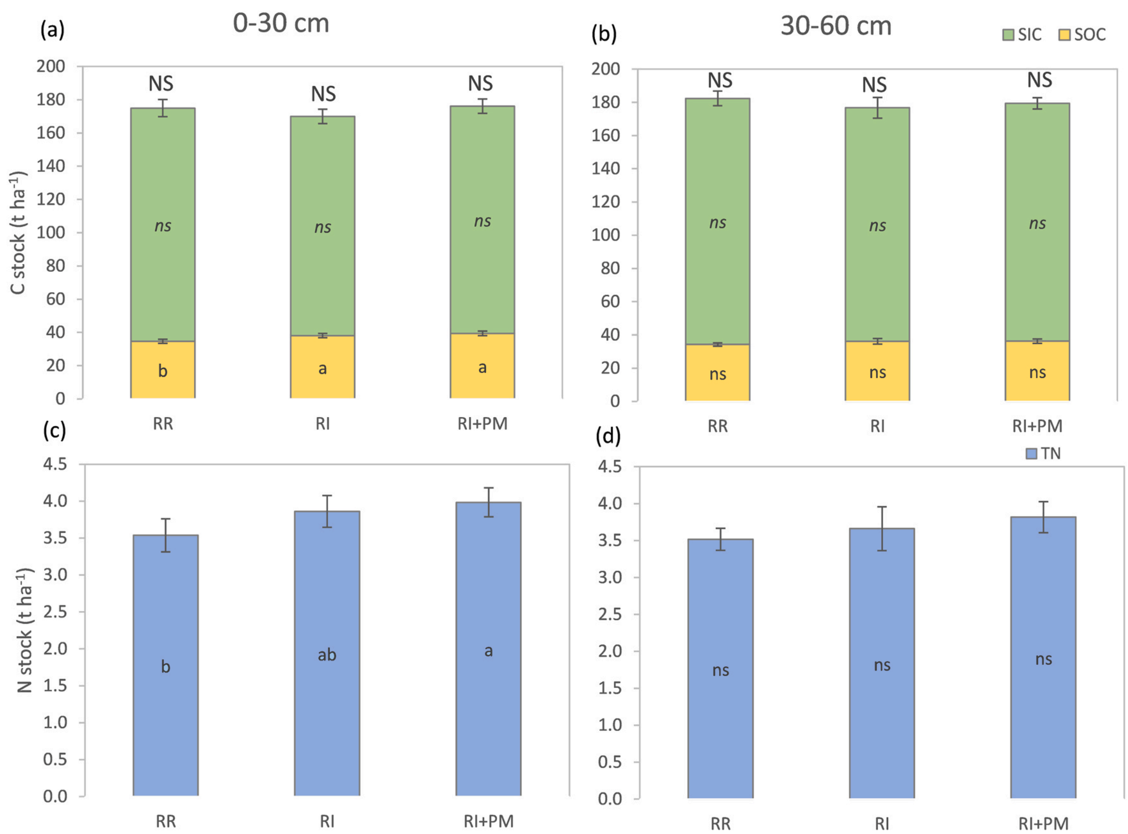

Fig. 4. SOC (a,b) and TN stock (c,d) at the 0–30 (a,c) and 30–60 cm (b,d) soil layer. Different letters represent a significant effect of residue management at p $\leq$0.05.

long-term (i.e., $\geq$ 28 yr) spring barley straw incorporation reduced the 0–20 cm BD of ca. 0.075 g cm^{-3} in sandy/sandy loam hard-setting Danish soils. On the contrary, Steponavičienė et al. (2022) did not find any effect on the 0–20 cm BD on loamy textured soil in Lithuania after 10-yr of residue incorporation. Like the other biomasses, crop residues are usually expected to have an indirect effect on BD. Indeed, by increasing the soil organic matter content, they can decrease the BD (Lal and Stewart, 1995). In our experiment, any effect of 55-yr of crop residue addition was found on BD neither in the tilled topsoil (i.e., 0–30 cm) nor in the subsoil (i.e., 30–60 cm).

It can be speculated that this was primarily due to their limited effect on SOC stock which will be further discussed below. The BD was even not further decreased by poultry manure addition. Xuan et al. (2022) recently found a significant effect when the residues were combined with fermented cattle manure on Chinese loamy soil where the BD decreased from 1.38 to 1.31 g cm^{-3}. It is worth noting that the poultry manure applied in our study adding about 40 kg N ha^{-1} and 410 kg OC ha^{-1} has previously been demonstrated to primarily act as a mineral N source rather than an effective organic matter input (Piccoli et al., 2020). Therefore, similarly to residues, its effect on soil structure and BD was negligible.

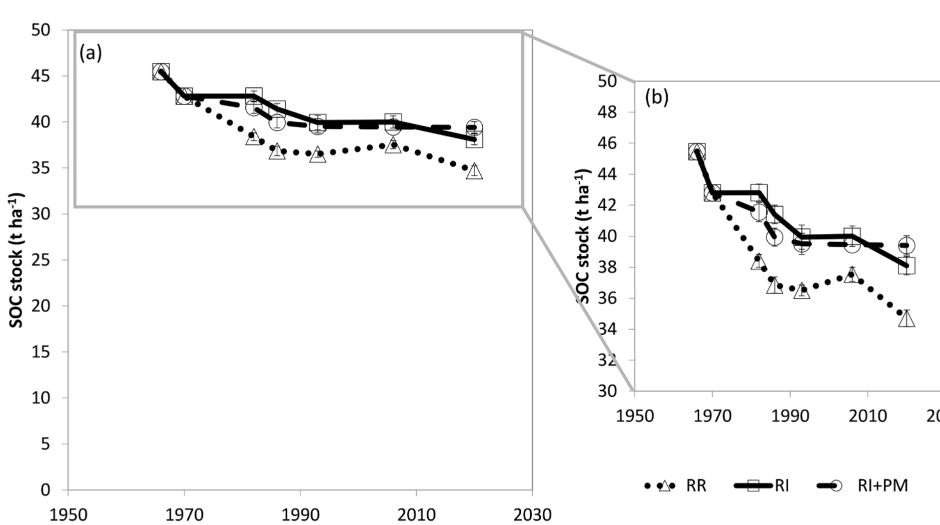

Fig. 5. Evolution of 0–30 cm SOC stock at the long-term experiment.

4.2. Soil carbon and nitrogen dynamics

Comparing the 0–30 cm SOC stock presented in this study with those previously published in the same experiments by Lugato et al. (2006) and Poeplau et al. (2017) a general decreasing trend in SOC stock can be evidenced from the start of the experiment to 1986 (Fig. 5 a). The apparent SOC loss seems greater in residual removal (-8.6 t ha^{-1}) than residual incorporation (-4.8 t ha^{-1}, irrespective of poultry manure addition) (Fig. 5 a). From 1986–2020 the gap between RR and RI/RI+PM maintained stable at about 4.1 t ha^{-1} (Fig. 5 b). Similar decreasing trend occurred in other sites in Europe. Shahbaz et al. (2019) evidenced a 38 % soil organic matter decline from 1956 to 1999 in a long-term experiment in Sweden that do not include residue incorporation and they demonstrated how root-derived C was not sufficient to counterbalance the SOC decomposition. Schjønning (2023) at the Rønhave site in Denmark noted a SOC decline in all compared treatments, including residue retention in an experiment started in 1966. The same author hypothesised that the soil C stock was at equilibrium (i.e., the C input was sufficient to counterbalance the SOC losses) before the start of the experiment due to a higher level of C input. Afterwards, the lower level of C input of the experimentation determined the SOC losses. The author also speculated that this still decreasing trend might suggest the path to the new equilibrium in soil C dynamics might be longer than what is usually assumed (e.g., 10/15 yr according to Jensen et al. 2022). The same conclusion may also be drawn by reading the SOC time series at our site. In the years before the experimentation, the field was conducted following the agricultural practices intensification that characterized the 60 s with probably higher C input, including organic fertilizers and alfalfa cropping, compared to what is applied nowadays. Therefore, the general SOC decline might represent the movement from a threshold level to another inside a cultivated agroecosystem, in particular a shift from a lower intensity (e.g., shallow non-inversion tillage with high level of C input) to a higher intensity system (e.g., moldboard ploughing with lower level of C input). Stewart et al. (2007) previously speculated that a soil C pool can stabilize at different SOC levels due to different agronomic-derived soil disturbances (e.g., soil tillage operations).

In 2020, following 55 years of experimental study, the retention of residues was found to mitigate the loss of SOC that occurred in the soil without residue incorporation. Indeed, the SOC content was greater by ~12 % in the tilled topsoil and 7 % in the subsoil compared to the residue removal practice. These estimates are in line with what was recently reported by Schjønning et al. (2023) who showed a 13 % SOC content increase due to residue incorporation at three sites in Denmark in the 0–30 cm soil layer. In our study, the SOC increase corresponded to SOC storage of 6 t ha^{-1} that was achieved as a result of ~ 127 t ha^{-1} residue-derived C input. Therefore, assuming that C sequestration was linear during the experimentation, an average conversion rate from residue-derived C to SOC can be estimated as 4.7 % which is comparable to what is reported in similar pedoclimatic conditions by Berti et al. (2016) (5 % conversion rate in 50 years of experiment) and in Flanders by Xu et al. (2021) (3 % conversion rate after two decades). Conversely, in other LTEs, Barber (1979) estimated a 11 % conversion rate in Indiana (USA), Kätterer et al. (2011) 15 % in Sweden and Plénet et al. (1993) 8.2 and 7.7 % in two locations in France.

The lower performances of studied soil in terms of crop residue humification might be due to several factors, first a higher mineralization rate. Unfortunately, to the best of our knowledge, no specific studies have been conducted on this topic in the Veneto region pedoclimatic conditions. Hence, we cannot exclude that other factors, like meteorological conditions in a climate change scenario, might have accelerated soil organic matter degradation, especially during the last 10/20 years. Despite the low effects of residue retention on SOC dynamics, they have also other benefits that cannot be overlooked such as an increase in macroporosity and available water for plants (Steponavičienė et al., 2022). Moreover, residues addition to the soil can stimulate their microbial decomposition, resulting in metabolites production such as polysaccharides (Ji et al., 2014) which can promote soil aggregate formation and, in turn, stabilize soil structure (Liu et al., 2005).

At the beginning of the trial, crop residue incorporation was also included in the experimental design together with poultry manure since the latter was considered a source of exogenous nitrogen able to stimulate residue decomposition by soil microorganisms (Bingeman et al., 1953) by narrowing the C:N ratio of carbonaceous residue biomass (Foth, 1951). However, in our study the RI+PM does not differentiate from RI alone, suggesting on the one hand that crop residue decomposition might not benefit from the poultry manure addition. It has been previously speculated that poultry manure fertilizer might have only a marginal effect on SOC accumulation (Piccoli et al., 2020) because the organic matter inside the poultry manure is less stable compared to other organic fertilizers, such as cattle manure (Velthof et al., 2000). Moreover, it is worth noting that only 1 t ha^{-1} of poultry manure was added to the plots receiving the RI+PM treatment corresponding to ~40 kg N ha^{-1}. Sainju et al. (2008) previously demonstrated how poultry manure can result in a significant SOC sequestration up to 510 kg C ha^{-1} yr^{-1} only with greater application doses (e.g., 100–200 kg N ha^{-1}). On the other hand, this may suggest that the C add each year with the PM (about 400 kg C ha^{-1}) was rapidly mineralized and/or the addition of N in mineral form with PM fostered the decomposition of insoluble organic fractions inside the native soil organic matter as a result of the priming effect (Kuzyakov and Bol, 2006). Indeed, despite the poultry manure addition to crop residue had a limited effect on soil organic matter dynamics, it increased the topsoil TN content, being RI+PM > RR of about 10 % which corresponds to 0.5 t TN ha^{-1}. Therefore, poultry manure, being an inexpensive source of N, can reduce the need for N fertilization, and, at the same time, give new insight into the circular economy rather than being disposed as a waste material (Sainju et al., 2010). To sustain crop production, poultry manure should be probably applied at higher N doses compared to mineral fertilizers. This is due to manure mineralization potential during the cropping season (Sainju et al., 2010). Although these study findings suggest that most of the N added with the PM will probably be in soluble/labile forms, special care should be taken in order to prevent nitrate leaching and, in turn, groundwater pollution.

In addition, as for other organic fertilizers, poultry manure application to the soil can stimulate fungi and root growth, increase microbial activity and its metabolites which, in turn, can promote stronger soil aggregation (Six et al., 2004).

It is worth noting that the application of N with mineral fertilizer with or without organic amendment (RI alone or RI+PM) had only marginal effects on SOC. N supply via synthetic fertilizer is usually considered to contribute to SOC stock by increasing the crop biomass and, in turn, the residue- and root-derived C input.

In this experiment, 120 kg N ha^{-1} resulted the N dose generating slightly greater C input and SOC content. By contrast, greater N doses seemed slightly detrimental in terms of SOC contents. This result is in line with the observations at the Morrow plots where the highest N dose was associated with the more serious SOC loss despite the dramatic escalation in the return of root biomass and crop residue in the soil (Khan et al., 2007). The same authors supported the thesis that N fertilization via synthetic fertilizer promotes increased crop yield but does not contribute to SOC sequestration.

Finally, the residue management did not impact SIC suggesting how the residue management may have any effect on the factors influencing its content in cultivated soils, e.g., mineral weathering (Bughio et al., 2017), soil acidity (Zamanian et al., 2018) and leaching (Sanderman, 2012).

5. Conclusions

The first starting hypothesis is here partially confirmed as after 55-yr of crop residue incorporation the SOC stock was greater of 6 t ha^{-1} in the

0–60 cm soil profile despite a general decresing trend in SOC stock was registered at the LTE.

The second starting hypothesis is partially rejected since the annual addition of 1 t ha^{-1} of poultry manure did not improve the SOC sequestration dynamics while increasing the TN content. Greater poultry manure application doses might be suitable for improving soil organic matter accumulation. However, poultry manure can be used as an alternative to mineral fertilizers, giving new insight into the circular economy.

CRediT authorship contribution statement

R. Polese:Writing – review & editing, Formal analysis, Data curation. **I. Piccoli**:Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. Berti**:Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Supplementary material

Average values of soil organic carbon (SOC), soil inorganic carbon (SIC), total soil carbon (TSC), total Kjeldhal nitrogen concentration and C:N ratio as affected by N dose and crop residue management are reported in Table S1.

Average values of soil organic carbon (SOC), soil inorganic carbon (SIC), total soil carbon (TSC) and total Kjeldhal nitrogen stocks as affected by N dose and crop residue management are reported in Table S2.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2024.106224.

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