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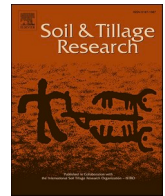
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Combined impact of no-tillage and cover crops on soil carbon stocks and fluxes in maize crops

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ABSTRACT

Soil plays a major role in the carbon cycle for both carbon stocks and respiration since soil organic carbon (SOC) is the most important carbon pool and soil CO₂ efflux is the largest source of carbon emissions to the atmosphere. The aim of this study was to understand how the combination of no-till (NT) and cover cropping (CC) influences both SOC and soil respiration. Soil respiration was measured in southwestern France from April to October at two distinct sites characterized by contrasting initial soil carbon contents. Each site included two adjoining maize fields in which conservation (NT+CC) and conventional (CT) practices were used. For soil with initial high SOC contents (> 50 t C ha⁻¹ in the 0–30 cm layer), SOC stocks at the 0–90 cm depth (NT+CC: 72.4 ± 10.6, CT: 68.9 ± 9.2 t C ha⁻¹) and respiration during the maize growing season (NT+CC: 0.57 ± 0.24, CT: 0.54 ± 0.26 g CO₂ m⁻² h⁻¹) were not significantly different for both practices. For soil with initial low SOC contents, SOC stocks at the 0–90 cm depth (NT+CC: 42.7 ± 5.5, CT: 29.7 ± 4.8 t C ha⁻¹) and respiration (NT+CC: 0.86 ± 0.32, CT: 0.50 ± 0.34 g CO₂ m⁻² h⁻¹) were higher with the NT+CC practices than with the CT practices. Due to higher cover crop biomass and root density, SOC mineralization and root respiration were enhanced. We showed a positive effect of conservation practices on the SOC stock in the upper layers but also in the deeper layers (60–90 cm) only in a low initial carbon content environment. At high SOC levels, the soil may have reached its carbon sequestration potential, or the time since practices were implemented was not long enough to observe the effects. Our study shows that the potential of NT+CC to sequester large amounts of SOC, enabling the mitigation of greenhouse gas emissions, strongly depends on initial SOC contents.

1. Introduction

Soil respiration is one of the largest natural carbon (C) fluxes (Friedlingstein et al., 2020) emitted from terrestrial ecosystems to the atmosphere, and it has been observed to increase over the last 50 years in relation to the increase in annual global mean temperature and climate change (Bond-Lamberty, 2010a; Suseela et al., 2012). In addition, soil organic carbon (SOC) is the largest organic carbon stock, representing approximately 2 400 Gt C stocked in the soil globally (Batjes, 1996). Emissions from land use change during 1901–2014 have been estimated at 35 ± 18 GtC (Arneeth et al., 2017; Nabuurs et al., 2022) and were most notably due to conversion from forest to croplands (Wei

et al., 2014), implying direct carbon loss from soil to the atmosphere (Nabuurs et al., 2022; Sanderman et al., 2017).

Anthropic activities exert a strong effect on soil respiration and SOC, particularly throughout conventional land management in agriculture (Abbas et al., 2020). Conservation management practices are considered a possible solution via SOC sequestration from the atmosphere (Chenu et al., 2019; Minasny et al., 2017). These practices have been defined by the Food and Agriculture Organization (FAO) (FAO, 2016) as a farming system that promotes minimum soil disturbance, maintenance of permanent soil cover and diversification of plant species. Compared to conventional practices, conservation practices tend to mitigate CO₂ fluxes (Zhang et al., 2021) and increase SOC stocks (Dignac et al., 2017;

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Lozano-García et al., 2020; Minasny et al., 2017; Xiao et al., 2021).

Under no-tillage (NT), an increase in SOC is observed in the upper fifteen centimetres (Haddaway et al., 2017; Mary et al., 2020). Conversely, Meurer et al. (2018) demonstrated that SOC accumulation under no-tillage can be overvalued in comparison to other tillage practices when focusing on the topsoil. SOC stocks also depend on the export of residues, which represent a large amount of C added to or removed from the soil carbon pool (Bolinder et al., 2020; Zhao et al., 2018). The review by Haddaway et al. (2017) on boreo-temperate regions concluded that no and reduced tillage increased the SOC stock in the topsoil (0–30 cm) by approximately 4.6 t C ha^{-1} over 10 years of cultivation, while no difference was detected across the soil profile investigated. Similar results were found for a long-term experiment in France, where different tillage techniques showed no significant impact on the SOC distribution across the soil profile investigated, but the SOC content increased substantially in the upper layer (0–10 cm) under no-tillage and more moderately in the underlying layer (15–40 cm) (Mary et al., 2020). Thus, no-tillage increases the SOC stock in soil surface layers (0–30 cm) but not in deep soil layers (50 cm and deeper).

In wheat–maize and soybean–maize rotations, in comparison to no-tillage, tillage increases soil respiration (Al-Kaisi and Yin, 2005; Balesdent et al., 1990; Buragienė et al., 2019; Franco-Luesma et al., 2020; Zhang et al., 2016). However, Pareja-Sánchez et al. (2019) showed that for irrigated maize, compared to conventional tillage, no-tillage increased soil respiration. Field experiments have determined that soil respiration strongly responds to tillage in the minutes following perturbation before returning back to its normal values a few hours later (Al-Kaisi and Yin, 2005). Tillage impacts soil structure by fractioning macroaggregates, allowing microorganisms to use SOC that was previously protected in macroaggregates and increasing CO_2 efflux (Six et al., 2000). The decrease in C emissions under no-tillage practices may derive from various mechanisms, such as a decrease in macroporosity (Wardak et al., 2022) and decreased soil disturbances (Mikha and Rice, 2004; Six et al., 2000). Reduced or no-tillage practices thus improve soil structure and related biological activities (Li et al., 2022; Six et al., 2002b).

Cover crops (CC) are also known to improve soil structural properties, water retention and carbon sequestration when combined with no-tillage (Blanco-Canqui et al., 2015, 2011; Huang et al., 2020). The literature indicates that cover crops are largely associated with an increase in the SOC stock, according to the time elapsed since the introduction of the practice (Blanco-Canqui et al., 2015; Constantin et al., 2010; Poeplau and Don, 2015). However, the increase in SOC stock under CC is generally observed at the 0–30 cm depth, and the accumulation capacities seem to decrease with time after the establishment of CC (Blanco-Canqui et al., 2022; Poeplau and Don, 2015). Recent studies have investigated the impact of CC on carbon sequestration through modelling (Kaye and Quemada, 2017; Launay et al., 2021), and their results confirm SOC accumulation capacities for cover cropping in the 0–30 cm soil layer. However, the impact of cover cropping on soil respiration remains to be investigated and requires more long-term studies.

Initial SOC stocks can also reduce the SOC sequestration capacities provided by cover crops, mainly due to SOC saturation (Chen et al., 2019; Six et al., 2002a). However, few studies have compared the impact of cover crops on SOC accumulation according to the initial SOC stock. Characterizing SOC accumulation capacities under contrasting initial SOC conditions is fundamental to assessing the impact of crop management practices on a variety of soils and environments.

Although NT and CC practices are well documented in the literature, it is unclear how combined conservation management practices affect soil respiration and organic carbon content. The combined effect of NT and CC has been found to increase SOC accumulation capacity more than NT or CC alone for maize crops in temperate ecosystems (Huang et al., 2020; Olson et al., 2014), but the combined effect of NT and CC practices on CO_2 efflux still needs to be investigated. The objective of this study was to investigate whether combined conservation crop

management practices (NT+CC) versus conventional practices (CT) systematically increase soil organic carbon content and induce less soil respiration according to the initial soil carbon content. To determine this, we present the results of two experiments conducted at sites differing in their initial soil carbon content, one with a higher SOC content and the other with a lower SOC content than the French national mean (50 tC ha^{-1}) for the 0–30 cm layer. Soil respiration and carbon content profiles (0–90 cm depth) were measured in two adjacent fields characterized by identical initial soil conditions before the implementation of conservation practices in one of the two fields.

2. Material and methods

2.1. Description of sites, soil and management practices

The experiment was carried out at two sites located in southwestern France, each site characterized by having higher and lower carbon contents than the French national mean of 50 t ha^{-1} for the 0–30 cm soil layer (Martin et al., 2021) and covered by maize grown in monoculture (Fig. 1). At each site, one field was under conservation practices (NT+CC) with no-tillage, cover crops and reduced inputs, while the second field was under conventional practices (CT) with tillage and bare soil between two cash crops.

The site with high SOC was located at Lalouquette (denoted VER; $43^{\circ}31'0.793''\text{N}$, $0^{\circ}15'40.878''\text{W}$, alt. = 221 m) and contained approximately 70 t SOC ha^{-1} . The soil here is defined as a Vermic Umbrisol according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2007) and as a Veracrisol according to the French Soil Classification (AFES, 2008), characterized by a neutral to slightly acidic pH and high organic matter content. This type of soil allows the transfer of humus at least at the 50 cm depth in the soil due to the intense bioturbation linked to the presence of earthworms. No irrigation is needed thanks to groundwater outcrop and capillary rise.

The site with low SOC was located at Estampes at 60 km from VER site (denoted LUV; $43^{\circ}24'38.057''\text{N}$, $0^{\circ}17'17.612''\text{E}$, alt. = 266 m) and contained approximately 30 and 25 t SOC ha^{-1} with the NT+CC and CT practices, respectively. The soil here is defined as a Stagnic Luvisol according to the World Reference Base for Soil Resource (IUSS Working Group WRB, 2007) and as a Luvisol according to the French Soil Classification (AFES, 2008), characterized by a textural horizon linked to the combination of clay, iron and organic matter, which is almost impermeable, leading to periods of hydromorphy with anoxia in winter and drought in summer. Luvisols are also characterized by a migration of

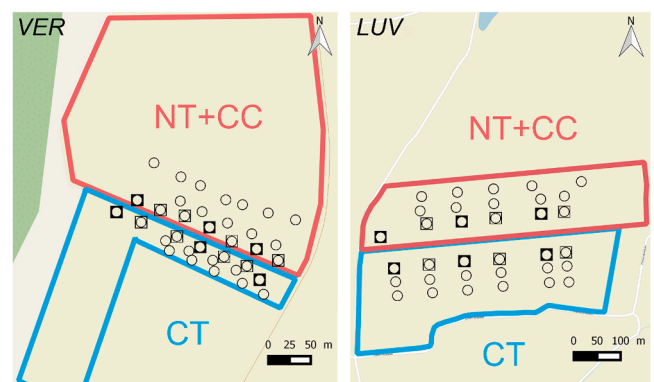


Fig. 1. Experimental design at Lalouquette (VER) in 2018 and Estampes (LUV) in 2019, with locations of measurements of soil respiration rate, soil sampling transects (empty squares) and profiles (full squares) on conservation (CT+CC) and conventional (CT) fields. Initial soil characteristics were identical before the implementation of conservation practices 12 and 19 years before the start of experiment for VER and LUV, respectively. SOC content environment was considered “high” at VER and “low” at LUV as compared to French national means.

clay into deep horizons and a high silt content that makes them vulnerable to heavy rainfall with surface crusting, a loss of permeability and increased runoff and erosion. Complementary information about the LUV and VER soils is detailed in Cueff et al., (2020, 2021).

The initial soil physicochemical property conditions were identical before the implementation of conservation practices for 12 and 19 years for VER and LUV, respectively.

Maize (*Zea mays* L.) was sown on 23 April and 9 May 2018 at the VER site (DKC5830 cultivar) and on 30 April and 29 March 2019 at the LUV site on NT+CC (P0900 cultivar) and CT (P0937 cultivar) fields, respectively. The row distance was shorter on the NT+CC fields (40 cm) than on the CT fields (80 cm), but the sowing density was similar for NT+CC (VER: 83000 seeds ha⁻¹; LUV: 90000 seeds ha⁻¹) and CT (VER: 78000 seeds ha⁻¹; LUV: 80000 seeds ha⁻¹) at both sites. In fact, the distance between plants in the same row was longer on the NT+CC field (20–30 cm) than on the CT field (10–15 cm). Hose reel irrigation was performed at the LUV site, where four irrigation treatments of 20, 30, 30 and 25 mm were carried out between 1 July and 15 August. Each irrigation pass lasted 6 days on average and was distributed across the field. A total of 105 mm and 120 mm were used on the NT+CC fields and CT fields, respectively. The VER site used rainfed maize.

For the NT+CC fields, Faba bean (*Vicia faba*) was grown as a cover crop from October 2017 to April 2018 and October 2018 to April 2019 at VER and LUV, respectively. Cover crops were destroyed by crushing during maize sowing and left in place as mulch at LUV; however, they were crushed two days after the maize was sown and a chemical treatment (2.5 L ha⁻¹ Glyphoflash®) was applied on 2 May at VER. For the CT fields at VER and LUV, three tillage events were carried out (24 and 27 April and 8 May 2018 at VER and 22, 28 and 29 March 2019 at LUV) with a maximum depth of 30 cm. Liming was performed at VER on the CT field (400 kg Ca ha⁻¹ on 5 April 2018) and at LUV on the NT+CC field (160 kg CaO ha⁻¹ on 15 March 2019).

Over the last 3–4 years, at both sites, nutrient amendments were lower at NT+CC fields than CT fields (Table 1).

2.2. Soil respiration measurements

Soil respiration was measured from 12 April to 4 October 2018 at VER and from 1 April and 25 October 2019 at LUV. Soil respiration measurements were conducted at 35 and 34 points at VER and LUV, respectively, along 3 transects in each field (Fig. 1). At VER, the distance between two points on the same transect was 30 m, and each transect was separated from the next transect by 10 m in the same field. At LUV, the distance between two points on the same transect varied from 75 m to 100 m, and the distance between each transect was 30 m. To prevent border effects, transects were at least 25 m away from borders at both sites.

Soil respiration was measured by an EGM-4 infrared CO₂ analyser (PP-Systems, Amesbury, USA) coupled with an SCR-1 soil respiration chamber (PP-Systems, Amesbury, USA) with a surface area of 78 cm² and a total volume of 1171 cm³. Pumpanen et al. (2004) found measurements with a PP-Systems CO₂ chamber to be more accurate without the use of collars, as in the present study. Moreover, Mills et al. (2011)

showed that the EGM-4 IRGA analyser was efficient at estimating soil respiration in field experiments. Soil respiration measurements were conducted between 11:30 am and 04:00 pm (GMT +01 Europe/Paris) between maize rows.

2.3. Soil analysis

Soil analysis was performed on soil samples taken from the 0–20 cm layers from one transect of 6 triplicates per field at VER and LUV (Fig. 1) to characterize the soil nutrient concentrations: total N was determined with the Kjeldahl method, available P was determined with the Olsen method in P₂O₅, K and Mg concentrations were determined with base exchange with ammonium acetate, and the C/N ratio was determined (LVES 32, Auch, France). Soil profiles were sampled in three zones per field (Fig. 1) from the 0–10 cm to 60–90 cm layers. Each sample was obtained using a polycarbonate column inserted in a steel cylinder. To minimize the spatial variability in the soil properties, a length of 20 m from the field boundary and between samples from the same field was maintained. Soil analysis was conducted at LAS INRAE (Arras, France) after soil samples were air dried and sieved at 2 mm to remove rocks and roots. These analyses provided information on pH, measured by a glass electrode of soil diluted at 1:5 in water, potassium chloride or calcium chloride; soil organic carbon (SOC) content, measured by dry combustion of soil sample; and cationic exchange capacity (CEC), measured by extraction of exchangeable cations with hexaamminecobalt trichloride. Bulk densities were then determined by the ratio of the dry weight of the undisturbed soil samples compared to the 250 cm³ cylindrical volume used (8 cm in diameter, 5 cm high) for the collection of each replicate at each depth investigated.

In addition, root density was estimated for the LUV site using a root auger cylinder (8 cm in diameter, 15 cm high). Six soil samples were collected in September 2019 in the first soil layer (0–15 cm) on both the NT+CC and CT fields. Samples were air dried for 24 h before sieving at 1 mm. Roots were then extracted manually and weighed.

2.4. Data analysis and statistics

The data processing, plotting and analysis were performed with R v4.0.5 (R Core Team, 2021) in Rstudio v1.4.1106 (RStudio Team, 2021). Graphical and statistical analyses were performed using the ggplot2 package by Wickham (2016) in addition to base R functions. Normality of distribution and homoscedasticity were tested before performing mean comparison tests (Student's t test or Mann–Whitney–Wilcoxon test). Differences among practices were considered significant at $P \leq 0.05$.

3. Results

3.1. Physicochemical soil characteristics

The main soil characteristics for the different layers from the surface to 90 cm depth are shown in Table 2. Significant differences were observed for pH and CEC in the entire soil profile at VER but only for pH

Table 1

Total nitrogen, phosphorus and potassium amendments at LUV and VER site for both NT+CC and CT fields from 2016 to 2019.

Nutrients kg ha ⁻¹	2016		2017		2018		2019		Total	
	NT+CC	CT	NT+CC	CT	NT+CC	CT	NT+CC	CT	NT+CC	CT
<i>VER</i>										
N	0	196	165	198	189	216			354	610
P	0	102	90	61	70	62			160	225
K	0	45	0	60	0	84			0	189
<i>LUV</i>										
N	200	184	190	180	0	200	151	214	541	778
P	10	0	10	55	0	55	5	55	25	165
K	0	120	0	120	8.5	0	0	200	8.5	440

Table 2

Soil physicochemical characteristics at the high (VER) and low (LUV) initial soil carbon content sites for NT+CC and CT crop practices: potential of hydrogen (pH), cation exchange capacity (CEC), and bulk densities for four soil layers from the surface to 90 cm depth. P value indicates whereas there is a significant difference between NT+CC and CT.

Depth cm	pH			CEC mmol kg ⁻¹			Bulk density g cm ⁻³		
	NT+CC	CT	P values	NT+CC	CT	P values	NT+CC	CT	P values
VER									
0 – 10	6.3 ± 0.0	6.5 ± 0.3	0.35	63.8 ± 1.5	79.3 ± 11.7	0.15	1.44 ± 0.11	1.39 ± 0.09	0.74
10 – 30	6.4 ± 0.1	6.8 ± 0.2	0.20	65.1 ± 2.1	81.9 ± 12.2	0.14	1.43 ± 0.11	1.43 ± 0.08	0.96
30 – 60	6.2 ± 0.1	6.9 ± 0.07	0.10	40.2 ± 4.5	56.9 ± 15.2	0.10	1.37 ± 0.17	1.43 ± 0.10	0.38
60 – 90	5.2 ± 0.1	6.5 ± 1.4	0.26	26.6 ± 1.8	36.8 ± 7.0	0.08	1.37 ± 0.17	1.44 ± 0.10	0.38
Mean	5.9 ± 0.6	6.7 ± 0.2	0.01	43.8 ± 16.7	58.2 ± 19.2	0.05	1.41 ± 0.14	1.42 ± 0.09	0.92
LUV									
0 – 10	5.8 ± 0.4	6.8 ± 0.2	0.02	48.0 ± 9.5	46.8 ± 5.7	1	1.50 ± 0.17	1.45 ± 0.19	0.58
10 – 30	6.0 ± 0.4	6.8 ± 0.2	0.60	44.6 ± 9.1	45.7 ± 6.2	0.88	1.49 ± 0.14	1.58 ± 0.10	0.06
30 – 60	6.6 ± 0.3	7.1 ± 0.1	0.04	44.7 ± 5	37.0 ± 6.5	0.19	1.45 ± 0.11	1.46 ± 0.12	0.82
60 – 90	6.3 ± 0.2	6.7 ± 0.2	0.33	49.3 ± 2.6	44.7 ± 7.4	0.66	1.45 ± 0.11	1.46 ± 0.12	0.82
Mean	6.3 ± 0.3	6.9 ± 0.2	3e-4	46.6 ± 2.3	42.6 ± 4.2	0.32	1.47 ± 0.13	1.48 ± 0.13	0.81

at LUV. Along the profile, soil pH varied from 5.2 to 6.9 and from 5.8 to 7.1 at VER and LUV, respectively. The NT+CC field soil was slightly more acidic than the CT field soil, displaying pH values 0.8 and 0.6 lower on average at VER in 2018 and LUV in 2019, respectively, which could have induced lower levels of microbial activity.

Among the different layers, CEC varied from 26.6 to 81.9 mmol kg⁻¹ and from 37.0 to 49.3 mmol kg⁻¹ at VER and LUV, respectively. Regarding the soil profile, CEC was 32.9% and 9.4% higher in the CT field soil at VER and in the NT+CC field soil at LUV, respectively. However, CEC was similar in each layer at both sites. CEC was more variable at VER in the CT field than at the other fields, likely due to liming.

Bulk density was not significantly different between the NT+CC and CT fields and varied between 1.37 ± 0.16 and 1.44 ± 0.11 g cm⁻³ and between 1.39 ± 0.09 and 1.43 ± 0.10 g cm⁻³, respectively, at VER (Table 2) and between 1.45 ± 0.10 and 1.50 ± 0.17 g cm⁻³ and between 1.45 ± 0.18 and 1.58 ± 0.09 g cm⁻³, respectively, at the LUV site.

Root density was measured at LUV only and was 0.34 ± 0.27 and 0.09 ± 0.11 mg cm⁻³ for the NT+CC and CT fields, respectively, and was significantly different between the two practices.

3.2. Soil organic carbon contents

The mean SOC content varied across the profile between 5.4 and

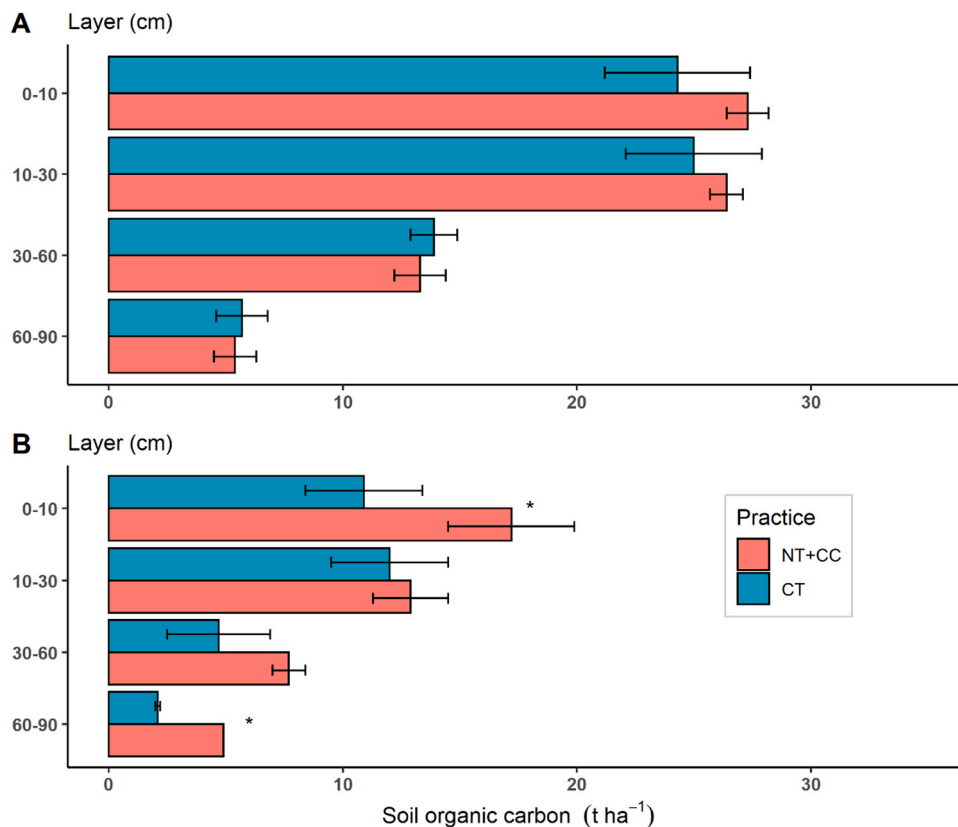


Fig. 2. Soil organic carbon content (t ha⁻¹) at VER (2018) site for high (A) and LUV site (2019) for low initial soil carbon content (B) for all layers investigated, from 0–10 to 60–90 cm depth. Error bars represent standard deviation and significant differences (*) are represented.

27.3 t ha⁻¹ and between 2.0 and 17.5 t ha⁻¹ at VER and LUV, respectively, with the lowest values being observed in the deepest layers and the highest values in the upper layers (Fig. 2). The total SOC content across the soil profile was 72.4 and 68.7 t C ha⁻¹ at VER and 42.7 and 29.6 t C ha⁻¹ at LUV in the NT+CC and CT fields, respectively. The content was similar in the NT+CC and CT fields at VER but significantly 43.8% higher in the NT+CC field than in the CT field at LUV. Higher values of SOC were observed in the uppermost 10 cm soil layer at both sites and were 12.3% and 57.8% higher in the NT+CC field than in the CT field at VER and LUV, respectively; however, this value was only significant at LUV. At LUV, the SOC stock in the deepest soil layer (60–90 cm) was significantly higher (2.8 t ha⁻¹, i.e., 130%) for NT+CC soil than for CT soil. No significant differences were observed at VER in any layer.

3.3. Soil nutrient characteristics

At both sites, the total N (Table 3) concentrations in the soil were significantly higher in the NT+CC fields than in the CT fields, although the cumulative level of N fertilization over the last 4 years was lower in the NT+CC field than in the CT field. Available K and Mg concentrations were also higher in the NT+CC field than in the CT field, but the differences were not significant. The concentration of available P was significantly higher in the CT fields than in the NT+CC fields soil for both sites; this was associated with a greater level of P fertilizer input.

At both sites, the mean C/N ratio for the 0–15 cm layer was similar in the NT+CC and CT fields (Table 3). For VER, the mean C/N ratio showed more variability in the CT field, with values as high as 13, which was not observed in the NT+CC field, while at LUV, the mean C/N ratio displayed more variability in the NT+CC field.

3.4. Seasonal changes in soil respiration according to crop management practices

For both crop management practices and both sites, as expected, the mean soil respiration rate increased from April to July and then decreased following temperature dynamics.

3.4.1. High soil organic carbon environment (VER in 2018)

At VER, the soil respiration rates varied between 0.09 and 1.38 g CO₂ m⁻² h⁻¹ and between 0.1 and 1.2 g CO₂ m⁻² h⁻¹ in the NT+CC and CT fields, respectively (Fig. 3a), and these rates were not significantly different (NT+CC: 0.57 ± 0.24 g CO₂ m⁻² h⁻¹, CT: 0.54 ± 0.26 g CO₂ m⁻² h⁻¹ on average). However, significant differences were found on four dates across the season. The NT+CC field soil respiration rates were 1.5 and 1.1 times higher than the CT field soil respiration rates on May 7 (13 days after sowing and 5 days after cover crop destruction for NT+CC and before sowing for CT) and July 17, respectively. The CT field soil respiration rate was 1.1 higher than the NT+CC field soil respiration rate on June 22, 2 days after N fertilization in the CT field, and on August 7.

Table 3

Soil nutrient concentrations as well as carbon-to-nitrogen ratio (C/N) for the 0–20 cm depth layer at the high (VER) and the low initial carbon content (LUV) sites for conservation (NT+CC) and conventional (CT) practices. Total N stands for total nitrogen, Available P, K and Mg indicates concentrations of phosphorus (P₂O₅), potassium (K₂O), and magnesium (MgO), respectively. P value indicates whereas there is a significant difference between NT+CC and CT.

Site	Total N mg kg ⁻¹		Available P mg kg ⁻¹		Available K mg kg ⁻¹		Available Mg mg kg ⁻¹		C/N	
	NT+CC	CT	NT+CC	CT	NT+CC	CT	NT+CC	CT	NT+CC	CT
VER	1773.1 ± 97.4	1491.3 ± 63.1	58.6 ± 12	92.8 ± 16.7	218.1 ± 55.9	186.7 ± 42.4	161.4 ± 41.8	103.0 ± 25.5	11.8 ± 0.5	11.8 ± 1.4
P value	7.9e-5		2e-3		0.27		0.42		0.98	
LUV	1463.7 ± 439.5	853.7 ± 213.6	7.5 ± 4.8	37.3 ± 19.7	99.5 ± 67.5	44.3 ± 71.8	71.7 ± 77.1	8.2 ± 4.4	8.9 ± 1.2	9.2 ± 0.6
P value	0.02		0.01		0.24		0.42		0.57	

3.4.2. Low soil organic carbon environment (LUV in 2019)

At LUV, the mean soil respiration rates varied between 0.32 and 2.29 g CO₂ m⁻² h⁻¹ and between 0.04 and 2.38 g CO₂ m⁻² h⁻¹ in the NT+CC and CT fields, respectively (Fig. 3b).

The average soil respiration rate throughout the maize growing season was significantly higher in the NT+CC field (0.86 ± 0.32 g CO₂ m⁻² h⁻¹) than in the CT field (0.50 ± 0.34 g CO₂ m⁻² h⁻¹). The mean NT+CC field soil respiration rate was significantly higher than the mean CT field soil respiration rate on all dates except on 13 August, when soil respiration rate in the CT field was higher, and on 19 July, when there was no significant difference in the rates between the two fields.

For a given field, when the soil respiration rates were averaged for all sampling dates throughout the growing season (four sampling dates in this period), the highest soil respiration rate recorded in the CT field was 0.73 gCO₂ m⁻² h⁻¹, while the lowest soil respiration rate recorded in the NT+CC field was 0.74 gCO₂ m⁻² h⁻¹. The highest soil respiration rates were observed during the irrigation period, suggesting soil moisture plays an important role in determining soil respiration.

4. Discussion

4.1. Impact of experimental design on soil respiration

The values of and variation in soil respiration rates measured in this study during the maize growing season were within the range of those reported in the literature for temperate ecosystems (Bond-Lamberty, 2010b). The EGM-4 IRGA analyser system coupled with SRC-1 is known to overestimate this flux by 33% both when collars are used and in fine wet sand (Pumpanen et al., 2004). According to Pumpanen et al. (2004), these overestimations can be considered negligible in most other cases. Heinemeyer et al. (2011) suggested that the use of collars could reduce soil carbon efflux by up to 30–50%, partly because of the damage to fine roots; thus, no collars were used in this study.

In the 2018 and 2019 experiments, sowing dates were different between the NT+CC and CT fields. At LUV in 2019, NT+CC sowing was performed almost a month after CT sowing. This difference in timing resulted in measuring soil respiration rates in soil with cover crops for the NT+CC field, while the CT field soil was bare in April. However, the large and systematic difference in the soil respiration rates between NT+CC and CT fields at LUV cannot be explained only by the shift in sowing date since the difference observed remained the same throughout the season (approximately 0.5 g CO₂ m⁻² h⁻¹). At VER in 2018, no difference was observed in the soil respiration rates throughout the maize growing season despite a 16-day difference in the timing of sowing. A significant difference was found at VER on 7 May 2018, with a higher soil respiration rate in the NT+CC field (two days before sowing at CT). This difference was undoubtedly due to the presence of mature cover crop residuals in the NT+CC field and bare soil in the CT field.

The same maize variety was sown at VER, but two different varieties were sown at LUV. However, this difference in varieties does not explain the systematic soil respiration differences between the two practices at LUV since the soil respiration rate was higher in the NT+CC field before

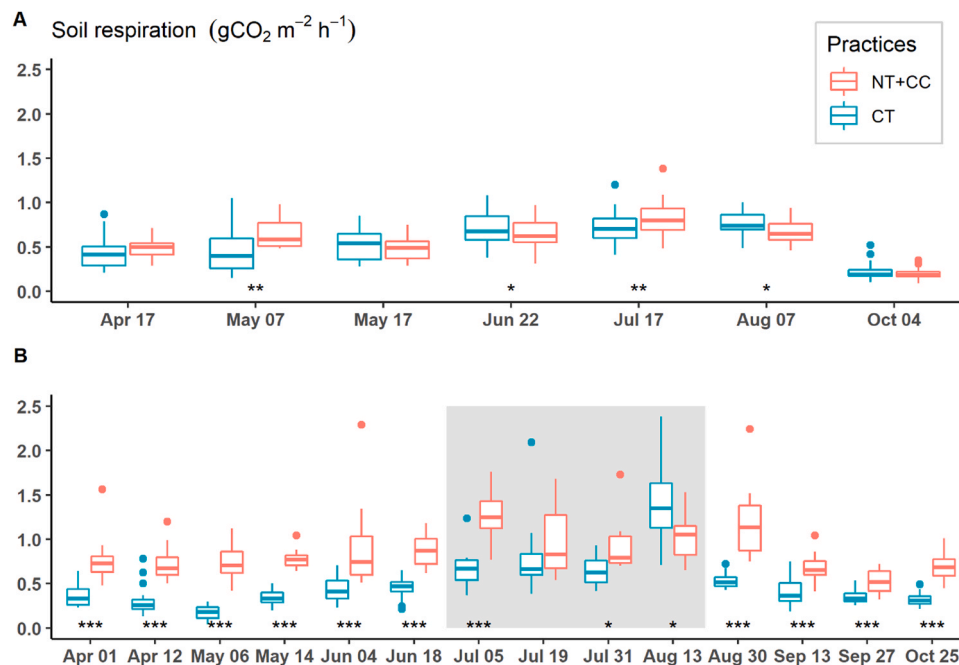


Fig. 3. Boxplots of the soil respiration rate from 17 April to 4 October 2018 at the high initial carbon content site VER (A) and from 1 April to 25 October 2019 at the low initial carbon content site LUV (B) for conservation (NT+CC) and conventional practices (CT). The grey area represents the irrigation period for LUV in 2019. Level of P values significance of are also indicated.

sowing in spring and after maize senescence in autumn.

The distance between rows was different for the two practices, 40 cm and 80 cm in the NT+CC and CT fields, respectively, but sowing density was similar for NT+CC and CT at both sites. In fact, the interplant distance was always greater in the NT+CC fields (approximately 30 cm) than in the CT field (approximately 10 cm). In addition, a higher root density was observed in the NT+CC field than in the CT field at LUV where soil measurements were conducted. This difference was more likely due to the presence of roots from cover crops and weeds in the NT+CC field as no cover crops and fewer weeds were observed in the CT field.

4.2. Impact of management practice strategy on soil organic carbon content

Fig. 4 summarizes the carbon inputs and outputs in the fields with the different practices and initial SOC contents. Soil carbon inputs from crop residues were considered similar for both the NT+CC and CT fields. Residual crop quantities were higher in the NT+CC fields than in the CT field because of cover crop residues. The biomass of crop residues from maize has been estimated to be approximately 2.5 t C ha⁻¹ (ICOS, 2021), while the biomass of Faba bean residues has been estimated to be approximately 3.5 t C ha⁻¹ (Alkhtib et al., 2016; Finney et al., 2016).

At VER (2018), no difference in SOC was found in the NT+CC and CT fields. However, the use of cover crops associated with NT+CC had been expected to increase inputs of organic matter to the soil from cover crop residues. According to Poeplau and Don (2015), most of the observations of annual changes in soil carbon due to cover cropping in comparison with fallow winter conditions have exhibited rates between 0 and 1 t SOC ha⁻¹ yr⁻¹ depending on the time since cover crop introduction, and the effectiveness of cover crops is reduced over time. The SOC content for the 0–30 cm soil layer was estimated at 53.7 t SOC ha⁻¹ and 49.2 t SOC ha⁻¹ for the NT+CC and CT fields, respectively. Thus, NT+CC enhanced the SOC content by 0.44 t SOC ha⁻¹ yr⁻¹, which is similar to the observations made by Poeplau and Don (2015) for the same time since cover crops were introduced. The increase in SOC at VER was similar to that estimated at LUV. In fact, the NT+CC field

enhanced the SOC content by 0.46 t SOC ha⁻¹ yr⁻¹ compared to that in the CT field at LUV. However, considering the whole soil profile (0–90 cm), these ratios were 0.36 and 0.82 t SOC ha⁻¹ yr⁻¹ at VER and LUV, respectively. The rate of SOC accumulation at LUV was 2.3 times higher than that at VER and higher than the mean rate estimate of SOC accumulation following CC described by Poeplau and Don (2015). These results suggest that cover crops at VER were not used for enough time to observe a positive impact on SOC. At LUV, the greater observed response than that observed in the literature was likely due to the combination of practices. Moreover, in addition to time since the CC practice was used, this higher estimation can be explained by the type of soil.

NT is assumed to increase the SOC concentration in the upper soil layers but to have a limited impact on the SOC concentration through the soil profile (Haddaway et al., 2017; Six et al., 2002b). At LUV, the NT+CC field sequestered higher quantities of C than the CT field in the top 30 cm layer, but surprisingly, this field also sequestered higher quantities in the 60–90 cm layer due to cover crop roots and the residues added to the NT+CC field. Carbon redistribution from the surface to deep layers by bioturbation or leaching of dissolved organic matter can add carbon to these layers. In fact, Luvisols are known to migrate clay through the soil profile to deep layers. This clay can be associated with organic compounds, which also explains part of the SOC accumulation in the deep layers. Another way to add carbon to these deep layers could also be through root exudates, which are an important soil organic carbon source for sequestration (Panchal et al., 2022). Erosion in conservation fields is also likely constrained by cover crops (Blanco-Canqui et al., 2015). Additionally, low oxygen availability can reduce SOC mineralization by microorganisms in deep layers.

Huang et al. (2020) demonstrated that the combination of NT and CC exerts a stronger impact on SOC accumulation than isolated practices for maize crops. Cover crops and no-till work simultaneously to increase SOC content, mainly through two mechanisms. First, these practices slow the decomposition of organic carbon stocked in the soil, likely by enhancing soil micro- and macroaggregates and protecting SOC from mineralization by microorganisms. Second, CC increases organic carbon input because of the higher biomass production in the field. Poeplau et al. (2021) found that among the most important factors determining

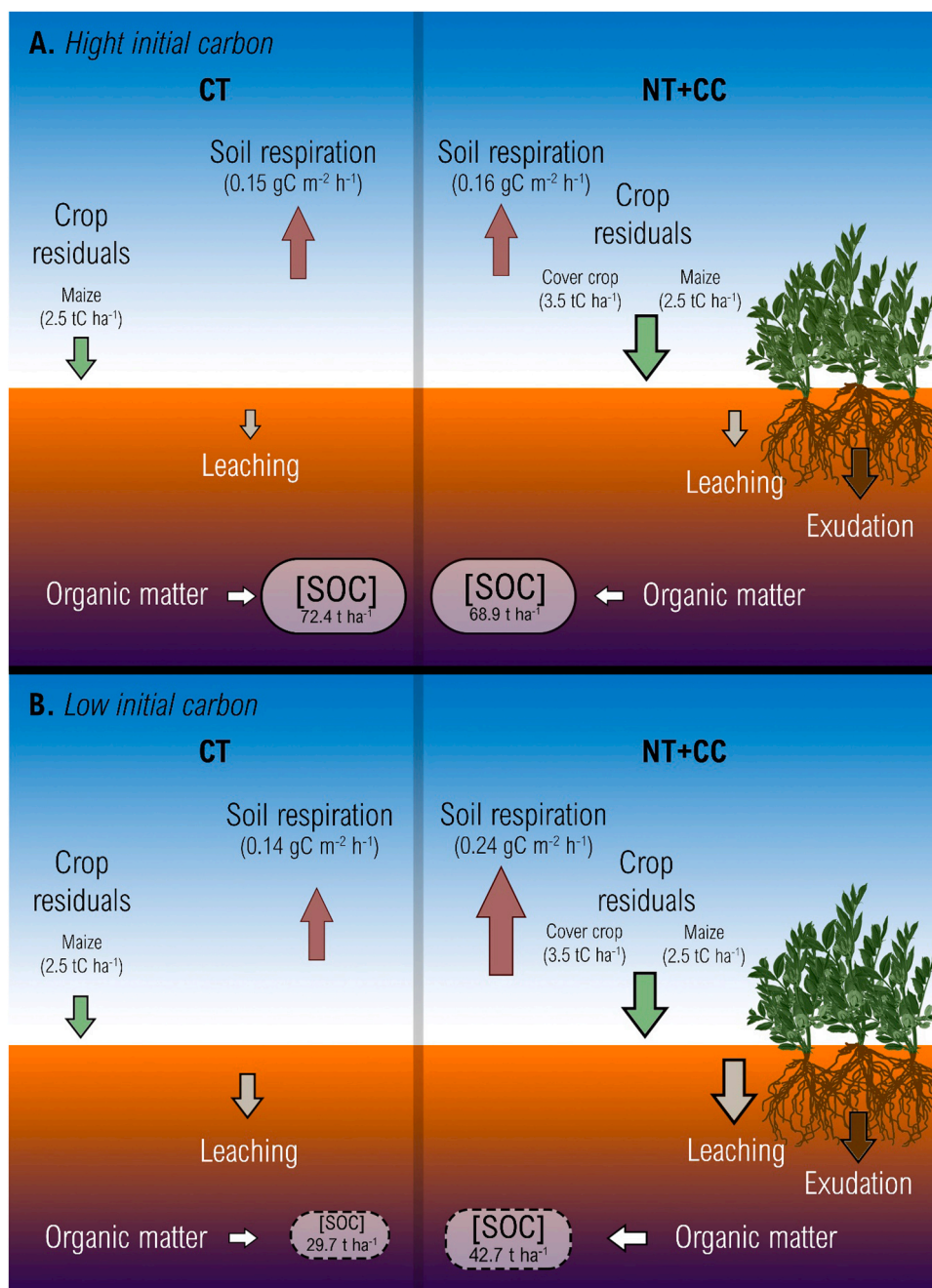


Fig. 4. Conceptual scheme of soil carbon fluxes and stocks for the high initial carbon content (VER) site (A) and for the low (LUV) one (B). The soil respiration value was the average of measurements from April to October 2018 and 2019 for the VER and LUV sites, respectively, and the SOC stocks values for the entire soil profile for conservation (NT+CC) and conventional (CT) fields. Cover crop and maize residuals were estimated from literature.

the average residence time of soil carbon, root carbon supply was the most effective factor that easily improved the soil when compared to clay, C:N, soil type, etc. In fact, higher root density was observed in the NT+CC field than in the CT field at LUV. General use of this practice would therefore allow the storage of additional C in the soil for a longer period, which would have a strong and long-lasting effect on climate change.

In contrast to the pattern at LUV, the absence of greater SOC accumulation in the NT+CC soil at VER can be explained by several factors: carbon saturation of soil, erosion and the time since the practice was introduced. First, a high initial stock of organic matter could reduce any additional capacity for SOC accumulation, meaning that the soil would have reached its carbon sequestration potential (Chen et al., 2019). This

could also be due to soil erosion, which pulls organic matter particles away from the field from wind and water, especially in the CT field rather than in the NT+CC field (Blanco-Canqui et al., 2015); however, in our case, the field was flat, and no difference was observed in the soil physical properties at VER (not shown). Last, if we consider the time since the practice was introduced, we hypothesized that our observations of SOC and soil respiration obtained in 2018 at VER would probably have taken place too early to see the positive effect. If so, then the SOC content of the soil in the CT field is likely to continue to decline, while the SOC stock in the NT+CC field is likely to increase and stabilize.

The simultaneous use of NT and CC leads to an increase in some soil physical properties, such as wet aggregate stability, enhancing SOC concentration, and water content (Blanco-Canqui et al., 2015), because

these practices lead to higher earthworm populations, which increase soil porosity and water storage capacities. All these benefits resulting from soil biodiversity (especially earthworms) are reduced with conventional practices such as tillage (Tsiafouli et al., 2015).

In addition, carbon mineralization is known to decrease with depth (Rey et al., 2008) so that substantial carbon migration to deep layers, as observed at LUV in the NT+CC field, can mitigate GHG emissions and thus climate change, as expected for the 4p1000 initiative project (Minasny et al., 2017).

4.3. Impact of management practice strategy on soil respiration

At both VER and LUV, soil respiration was the highest in July and August, coinciding with the period of maximum air and soil temperatures, maize growth rates and irrigation (only at LUV). At LUV, the impact of irrigation on soil respiration was illustrated on 19 July, when the irrigation system was operating on the NT+CC field. Soil respiration was significantly higher in the areas that were irrigated a few minutes before soil respiration measurements were obtained than at those not yet irrigated. This result suggests that microorganisms were less active due to water stress or that irrigation water allows dissolved organic matter and nutrients to leach into soil, particularly through micropores, thus reactivating soil microorganisms that could have been previously starved of carbon and substrate, but this reaction may not be instantaneous and could be limited in duration. Conversely, saturation of surface layers can limit both respiration and emissions by leading to anaerobic conditions and limiting gas diffusion. Laboratory studies have demonstrated that soil moisture modulates soil respiration, reducing it when it is high by limiting CO₂ diffusion (Linn and Doran, 1984) or when it is low by slowing aerobic decomposition and inhibiting microbial and root activity (Yuste et al., 2003) due to diffusional limitation of C substrate and nutrients in the porous medium.

Roots and rhizospheric respiration can account for between 12% and 43% of total soil respiration in croplands (Hanson et al., 2000), with important variation due to the different methods employed to estimate this parameter and the great variability in climate among croplands (Raich and Mora, 2005). Thus, high root activity associated with high maize development likely contributed to higher soil respiration in summer. In addition to root respiration, another large primary source of soil CO₂ emissions was the decomposition of SOC by bacteria and fungi. The NT+CC field soils were more acidic and contained more organic C than the CT field soils. However, CEC was higher in the CT field at VER than at LUV but higher in the NT+CC field at LUV, considering the soil profile investigated, which could reflect smaller proportions of fungal community compositional turnover (Glassman et al., 2017).

At VER, although additional C was supplied to the NT+CC field through cover crop residues, the soil respiration and SOC of the two fields were similar, whereas a result such as that observed at LUV was expected, i.e., greater soil respiration (Fig. 4). Thus, the additional carbon provided to the field by the cover crops was not detected in either the flows or the stocks. In contrast, at LUV despite enhanced CO₂ efflux from the soil, in comparison to the CT fields, the NT+CC fields had higher SOC contents. Greater carbon loss due to higher soil respiration was likely compensated by increased C inputs linked to the presence of cover crop residues with the NT+CC practice. Pareja-Sánchez et al. (2019) observed similar results for a similar duration of practice, i.e., approximately 20 years. Hu et al. (2015) concluded that lower carbon emissions imply greater C sequestration in soils, mitigating GHG effects. This was clearly not the case at LUV.

At LUV, total N and SOC were higher in the NT+CC field soil than in the CT field soil, suggesting that a large amount of total N was in the organic form in the former compared to that in the latter. Most organic N forms are not directly available and need to be mineralized before uptake and use by plants. Mineral N application was delivered at a higher rate in the CT field than in the NT+CC field so that a higher soil mineral N availability under CT could have decreased the need for

microorganisms to mineralize SOC and thus reduced soil respiration (Pareja-Sánchez et al., 2019).

Most studies assume that in comparison to NT, tillage leads to higher C efflux for maize crops (Bogužas et al., 2018; Buragienė et al., 2019; Zhang et al., 2016), mainly because the fractioning soils lead to easier access to soil organic carbon for microorganisms and thus mineralization (Six et al., 2000). For example, Al-Kaisi and Yin (2005) compared different types of tillage (strip-tillage, deep rip, chisel and mouldboard plough), including no-tillage, and found that tillage increased soil respiration for irrigated maize in a continental climate. However, a portion of the measurements in the Al-Kaisi and Yin (2005) study were obtained during a very short period of time after tillage was performed (1–2 min); thus, high values of soil respiration were observed immediately after tillage because of the sudden accessibility of SOC and dioxygen for microorganisms (Six et al., 2002b).

The accumulation of organic carbon in soils is one of the best ways to mitigate GHG emissions. However, NT practices in temperate climates for various crops, including maize, can produce higher N₂O emissions, which can return the GHG balance to a negative ratio (Six et al., 2002b). Thus, although it has been asserted that soil disturbance by tillage practices promotes soil CO₂ emissions (Al-Kaisi and Yin, 2005; Balesdent et al., 1990; Bogužas et al., 2018; Buragienė et al., 2019), this is clearly not always the case, as demonstrated by Pareja-Sánchez et al. (2019) and the findings of this study.

The discrepancy between some literature results and our results might also be explained by the time period since conservation practice conversion took place. The mean duration of conservation practices in most of the studies was approximately 8 years, which is less than that in the present study (12 and 19 years at VER and LUV, respectively). The time that a practice has been used likely influences soil carbon dynamics. Poeplau and Don (2015) have demonstrated that the soil carbon stock significantly changes over time after cover crops were first used. These mechanisms are likely linked to increased soil quality that acts as a positive regulatory feedback mechanism on microbial communities and soil structure, thus increasing soil CO₂ efflux.

5. Conclusion

Our study demonstrated that conservation practices can enhance soil organic carbon stocks despite an increase in soil carbon efflux. The combined practice of cover cropping and no tillage significantly enhanced the SOC content, as is already known to occur in upper soil layers, specifically in the deepest layers, which is particularly effective for mitigating greenhouse gas emissions. Cover crop practices directly influence soil respiration by enhancing root density, notably in the first soil layer. However, despite this additional carbon flux, the accumulation that occurs in soil through cover crop biomass production enhances soil organic carbon stocks.

However, this conclusion is not confirmed for a high soil organic carbon environment, suggesting that this positive impact on climate change mitigation should be specified for a variety of soil types. In fact, the soil can sequester more or less organic carbon, notably according to available silt and clay. If it reaches its carbon potential, then it can scarcely sequester more organic carbon. Moreover, the time since practices are implemented can also play a major role as well as the history of the land use.

The use of conservation practices compared to conventional practices exerts an important impact on carbon dynamics in maize croplands, especially when soils feature significant carbon sink capacities. The great carbon accumulation capacity of croplands can thus significantly impact CO₂ emission mitigation and climate change.

As croplands are not usually homogeneous in terms of either soil composition or physical structure, a spatial analysis of soil respiration heterogeneity linked with organic matter quality, topography and pedoclimatic variables should be conducted in the future. Additionally, the partitioning of soil respiration into heterotroph and autotroph

respiration could facilitate the elucidation of the role of microorganisms and the effect of roots on total soil respiration. Additionally, studies on the entire soil profile rather than on only the 0–40 cm layer as well as on root densities are needed to better understand SOC sequestration in conservation agriculture. A better understanding of how N₂O and CH₄ fluxes act conjointly or not with CO₂ using conservation and conventional practices is also important to consider for mitigating climate change.

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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

Soil respiration, temperature and moisture data are available on the CESBIO Environmental Information System (SIE) at https://sie.cesbio.omp.eu/detail_releve.php?id=61 and https://sie.cesbio.omp.eu/detail_releve.php?id=60 for VER site and LUV site, respectively.

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Appendix A. Supplementary data

These data include the climatic conditions of the two experiments in 2018 and 2019, detailed relationships between soil respiration and soil temperature and moisture and finally soil microorganism abundance in relation to practices and soil respiration.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.still.2023.105782](https://doi.org/10.1016/j.still.2023.105782).

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