What is the stability of additional organic carbon stored thanks to alternative cropping systems and organic wastes products application? A multi-methods evaluation

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Abstract

The implementation of agroecological practices often leads to additional soil organic carbon storage, and we have sought to assess the biogeochemical stability of this additional carbon. To achieve this, we implemented a multi-method approach using particle size and density fractionation, Rock-Eval® thermal analyses and long-term incubation (484 days), that we applied to topsoil samples (0-30 cm) from temperate luvisols that had been subjected, in > 20 years long-term experiments in France, to conservation agriculture (CA), organic agriculture (ORG) and conventional agriculture (CON-LC) in La Cage experiment, and to organic wastes products (OWPs) applications in QualiAgro experiment, including biowaste composts (BIOW), residual municipal solid waste composts (MSW), farmyard manure (FYM) and conventional agriculture without organic inputs (CON-QA). The additional carbon resulting from agroecological practices is the difference between the carbon stock of the bulk soil, physical fractions or carbon pools in a soil under the agroecological practices and that of the same soil under a conventional practice as control. The incubations provided information on the additional carbon stability in the short term (i.e., MRT <2 years) and showed that the additional soil organic carbon mineralized faster than the carbon in the conventional control at La Cage but slower at QualiAgro. In OWPs-treated plots at QualiAgro, 60-66% of the additional carbon was stored as mineral-associated organic matter (MAOM-C), and 34-40% as particulate organic matter (POM-C). In CA and ORG systems at La Cage, 77-84% of the additional carbon was stored in MAOM-C, versus 16-23% as POM-C. Management practices hence influenced the distribution of additional carbon in physical fractions. Utilizing the PARTYSOC model with Rock-Eval® thermal analysis parameters, we found that most, if not all, of the additional carbon belonged to the active carbon pool (MRT ~ 30-40 years). In summary,

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our comprehensive multi-methods evaluation indicates that the additional soil organic carbon is less stable over decadal and pluri-decadal time-scales compared to soil carbon under conventional controls. Our results show that particle size and density fractions can be heterogenous in their biogeochemical stability. On the other hand, although the additional carbon is mainly associated with MAOM, the high proportion of this carbon in the active pool suggests that it has a mean residence time not exceeding ~50 years. On the other hand, agroecological practices with equivalent additional carbon stocks (MSW, FYM vs CA) exhibited a higher proportion of additional carbon in POM-C under MSW (40%) and FYM (34%) compared to CA (16%), which suggests a high chemical recalcitrance of POM-C under OWPs management relative to conservation agriculture. Additional soil organic carbon deriving from organic wastes, i.e., biomass that has been partially decomposed and transformed through its processing prior to its incorporation in soil, would be more biogeochemically stable in soil than that deriving directly from plant biomass. The apparent contradictions observed between method can be explained by the fact that they address different kinetic pools of organic carbon. Care must be taken to specify which range of residence times is considered when using any method intending to evaluate the biogeochemical stability of soil organic matter, as well as when using the terms stable or labile. In conclusion, the contrasting biogeochemical stabilities observed in the different management options highlight the need to maintain agroecological practices to keep these carbon stocks at a high level over time, given that the additional carbon is stable on a pluri-decadal scale.

Keywords: *soil organic carbon, additional carbon, agroecological practices, Rock-Eval®, biogeochemical stability, incubation, physical fractions.*

1 Introduction

Soil organic matter (SOM) plays a crucial role in the functioning of terrestrial ecosystems and can contribute to mitigate climate change. A minor change of soil organic carbon (SOC) content can make a significant difference to global climate because soil contains more carbon than vegetation and atmosphere combined (Lal, 2004). The 4p1000 initiative encourages the implementation of agricultural practices that increase and/or maintain soil carbon stocks (www.4p1000.org, Rumpel et al., 2020). At the field scale, changes in SOC stocks result from an imbalance between C inputs (crop residues, litter, root exudates, exogenous organic matter such as organic wastes products (OWPs)) and C outputs from the system due to crop residue export, SOC mineralization, leaching, or erosion (Lal, 2018). Although some agricultural practices can reduce mineralization rates (e.g., reduced tillage, see review by Haddaway et al., 2017), it is generally accepted that the most effective way to increase SOC stocks is to increase carbon inputs (e.g., Virto et al., 2012; Autret et al., 2016; Fujisaki et al., 2018; Chenu et al. 2019). This can be achieved by increasing biomass production in the field and residue return (e.g., cover

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crops, Poeplau and Don, 2015; Autret et al., 2016), or by mobilizing external carbon resources such as OWPs (Peltre et al., 2012; Paetsch et al., 2016).

The implementation of selected agroecological practices and systems such as conservation agriculture, agroforestry, OWPs application allows for additional carbon storage in soils (Peltre et al., 2012; Autret et al., 2016; Paetsch et al., 2016; Pellerin et al., 2019; Bohoussou et al., 2022). The additional carbon storage linked to agricultural practice B is the difference between the carbon stock in a soil under practice B and that of the same soil under a reference practice (Pellerin et al., 2019). This additional carbon storage is not necessarily the result of recent carbon inputs, but can also include the legacy carbon. However, knowledge on the biogeochemical stability of this additional carbon is lacking, questioning the reversibility of this storage. The carbon sink effect will indeed be more effective if the additional carbon storage is realized in the form of persistent organic carbon (OC) and not in the form of labile OC. We propose to evaluate and compare the biogeochemical stability of additional organic carbon following implementation of various agroecological practices.

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Several methods have been reported in the literature to assess the organic carbon temporal stability in soils. These methods isolate kinetic pools or carbon fractions with contrasting mean residence times (MRT), e.g., particle size fractionation, Balesdent, 1996; density fractionation, Sollins et al., 2006; sequential extraction, Heckman et al., 2018; thermal analysis, Barré et al., 2016 and incubation, Schädel et al., 2020. Physical fractionation is probably the most used method so far to evaluate SOM stability. Physical fractionation methods isolate fractions based on size, density, or a mixture of both (Chenu et al., 2015). In a study comparing several fractionation methods, Poeplau et al. (2018) found that particle size fractionation was well suited to isolate particulate organic matter (POM) fractions from mineral associated organic matter (MAOM) with contrasting MRT. Fractionation of SOM into POM and MAOM components can reveal insights about the sources and stability of SOC (Kim et al., 2022). However, some studies have shown that SOC fractionation methods fail to accurately separate stable SOC from active SOC, and in particular that the isolated MAOM fractions are mixtures of labile SOC (MRT of months to year) and stable centennial SOC (Balesdent et al. 1987; Jastrow et al., 1996; Sanderman et al., 2013; Torn et al., 2013; Balesdent, 1996; Hsieh, 1992; von Lützow et al., 2007; Sanderman and Grandy, 2020). This may be due to methodological challenges as much as the fact that there are multiple pathways for SOM formation and stabilization (Cotrufo et al., 2013; Sokol et al., 2019).

Thermal analysis techniques, long used in petroleum exploration and clay mineralogy, offer a promising alternative or complement to physical and chemical fractionation methods, and are increasingly applied to studies of SOC stability (Peltre et al., 2013; Plante et al., 2009). Indeed, several parameters obtained using thermal analysis are strongly related to SOM biogeochemical stability (Barré

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et al., 2016; Poeplau et al., 2019). However, these parameters do not allow us to separate the kinetic carbon pools (Schiedung et al., 2017). And so, recently, Cécillon et al. (2018, 2021) developed a machine-learning model, called $\text{PARTY}_{\text{SOC}}$, showing that Rock-Eval® parameters can be used to predict the fraction of SOC that is stable at a centennial timescale. Kanari et al. (2022) evidenced that SOC fractions calculated using $\text{PARTY}_{\text{SOC}}$ matched the stable (MRT >100 years) and active (MRT ~ 30-40 years) OC pools of the AMG model, a model widely validated to simulate SOC stock evolution in French and European croplands (Clivot et al., 2019; Bruni et al., 2022). As a result, one can consider that a Rock-Eval® analysis associated to the $\text{PARTY}_{\text{SOC}}$ model allows for the quantification of carbon fractions that are stable at a centennial timescale and active *sensu* AMG model.

The incubation method is, however, the only direct test for the biological stability of SOC, that results from chemical resistance to decomposition and/or organo-mineral associations and/or inaccessibility of organic substrates to microbial decomposition. Long-term incubations (months to years) may diverge from the conditions prevailing in the soil profile but provide insights into the potential decomposability of slower-cycling SOC (e.g., Schädel et al., 2014). In early laboratory incubations, fast-cycling C respiration dominates total respired SOC, but rapidly declines, while slow-cycling SOC accounts for most of the respired SOC after the fast SOC pool is depleted.

These different methods do not separate similar carbon kinetic pools. Indeed, the incubation method isolates carbon with MRT ranging from days to years (Schädel et al., 2014) while others isolate carbon with longer MRT (decades to centuries) (Cécillon et al., 2018, 2021, Balesdent, 1996). Thus, a multi-method approach will further improve our knowledge of the biogeochemical stability of SOC in the short (<2 years), medium (2-50 years) or long term (>50 years). The objective of this study was to evaluate the biogeochemical stability of additional SOC stored upon the implementation of carbon storing agroecological practices using a multi-method approach. To do so, we characterized SOM using particle size and density fractionation, Rock-Eval® (RE) thermal analysis and incubation in soil from plots managed using various agroecological practices such as addition of OWPs (composts and farmyard manure) and alternative cropping systems including no tillage, permanent cover crop and the introduction of legumes in the rotation. The application of OWPs is likely to provide organic matter (OM) that has been pre-stabilized by the storage (manure) or composting process and is hence less decomposable than the fresh matter provided by plant biomass in alternative cropping systems. Then, we hypothesized (i) that the biogeochemical stability of additional SOC depends on the management practices implemented and (ii) that the additional SOC originating from OWPs would be more stable than that directly originating from plant biomass, but, (iii) overall, that the additional SOC would be less stable than the SOC stored in the conventional controls.

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2 Materials and methods

2.1 Field Site and soil sampling

This study focuses on two French long-term experiments (LTEs) developed on Luvisols in the same region, where agroecological practices including conservation agriculture, organic agriculture and OWPs application (composts and manure) were implemented.

La Cage experiment is conducted in Versailles (48°48'N,2°08'E, alt 120 m). During the 21 years of experimentation, the mean annual temperature and precipitation were 11.6 °C and 633 respectively. The soil is a well-drained deep Luvisol (IUSS Working Group WRB, 2015). The field experiment is arranged in a randomized complete block design, divided into two blocks, themselves divided into four plots for each cropping system. Each plot is divided into two subplots of 0.56 ha, so that two different crops of the crop rotation are present each year, wheat being grown every year in one of the two subplots (Autret et al., 2020). A detailed presentation of crop rotations, soil management and fertilization were given by Autret et al. (2016). The 4 year's crop rotation mainly consisted of rapeseed (*Brassica napus L.*), winter wheat (*Triticum aestivum L.*), spring pea (*Pisum sativum L.*) and winter wheat.

- Conventional agriculture (CON-LC) is characterized by a soil and crop management representative of the Paris Basin cereal production, with annual soil ploughing, the absence of organic amendment, a mineral N fertilization (average rate = 143 kg N ha^{-1} yr^{-1}) and a systematic use of pesticides.
- Conservation agriculture (CA) includes a permanent soil cover, initially fescue (*Festuca rubra*) and since 2008 alfalfa, grown under the main crops, except pea. In the rotation, rapeseed is replaced by maize (*Zea mays L.*) in CA and direct seeding is performed.
- Organic agriculture (ORG) is characterized by alfalfa-alfalfa-wheat-wheat rotation with annual soil ploughing and no synthetic fertilizers nor pesticides.

The QualiAgro experiment is located at Feucherolles, 20 km west of Versailles (48°52′N, 1°57′E, alt 150 m). During the 21 years of experimentation, the mean annual temperature and precipitation were 11.0 °C and 614 respectively. The soil is a Luvisol (IUSS Working Group WRB, 2015). The crop rotation mainly consisted of wheat and maize (Peltre et al., 2012). It is a field experiment conducted in collaboration with INRAE and Veolia Environment Research and Innovation since 1998, on which composts of OWPs are applied every 2 years for a dose equivalent to ~4 t C. ha^{-1} from 1998 to 2013 and ~2 t C. ha^{-1} from 2015 to 2020. The unit plots are 10 x 45 m^2. Each treatment has 4 replicates and OWPs are applied every two years on wheat stubble. Soils are ploughed every year on this experimental site. Since 2015, wheat and maize residues are buried in the soil. Four treatments are considered in this study.

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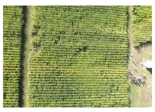
- Conventional agriculture (CON-QA): is characterized by a soil and crop management representative of the Paris Basin cereal, the absence of organic amendment, a mineral N fertilization (average rate = 167 kg N ha^{-1} yr^{-1}).
- Biowaste compost (BIOW): composting of the fermentable fraction of selectively collected household waste, mixed with green waste;
- Municipal solid waste compost (MSW): composting of the residual fraction of household waste after selective collection of packaging;
- Farmyard manure (FYM) which represents a reference amendment.

At both sites, four replicate plots were available per treatment. From each plot, 3 sub-samples were taken from the topsoil 30 ± 1 cm (in September 2019 at QualiAgro and in November 2020 at La Cage), thoroughly mixed and combined into one sample. The samples were sieved to 4 mm, homogenized, the plant material was removed and the soil was oven dried at 35°C for 72h before particle size and density fractionation and RE thermal analysis.

Table 1 Soil organic carbon (SOC), soil organic nitrogen (SON) and C/N measured in topsoil. Values in brackets are standard deviations. CON-QA: conventional agriculture without organic inputs, MSW: municipal solid waste compost, FYM: farmyard manure, BIOW: biowaste compost, CON-LC: conventional agriculture, ORG: organic agriculture and CA: conservation agriculture.

Site	Soil textured	Agricultural Practices	SOC content g.kg^{-1}	SOC stocks t C. ha^{-1}	SOC gain (%)	SON g.kg^{-1}	C/N
La Cage 	Luvisol 17% Clay 58% Silt 25% Sand	CON-LC	9.82 ± 0.48	42.22 ± 2.08	-	1.01 ± 0.07	10.58 ± 1.58
		ORG	10.39 ± 0.42	44.66 ± 1.80	6	1.09 ± 0.03	9.52 ± 0.12
		CA	13.30 ± 1.05	57.17 ± 4.53	35	1.29 ± 0.10	10.29 ± 0.28
QualiAgro 	Luvisol 15% Clay 78% Silt 7% Sand	CON-QA	9.92 ± 0.63	39.31 ± 2.49	-	0.97 ± 0.08	10.35 ± 1.61
		MSW	13.84 ± 0.16	54.03 ± 0.59	33	1.35 ± 0.04	10.26 ± 0.42
		FYM	13.91 ± 0.37	54.77 ± 1.40	42	1.36 ± 0.02	10.21 ± 0.37
		BIOW	16.04 ± 0.68	63.17 ± 2.56	64	1.62 ± 0.01	9.87 ± 0.41

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2.2 Calculation of SOC stocks and additional carbon stocks

SOC stocks were calculated at equivalent soil mass in both long-term experiments. Thus, at QualiAgro the SOC stock was calculated by multiplying the SOC content by bulk density (data provided by QualiAgro) and was normalized to a depth of 10 cm (factor 10^{-3}) (reference soil mass of 3963 kg. ha^{-1}). Bulk densities between 1998 and 2019 increased significantly in all plots. We calculated the additional soil thickness required to achieve this equivalent soil mass in treatments with lighter tilled layers as described by Ellert and Bettany (1995):

$$T_{add} = \frac{((M_{soil\ equiv} - M_{soil\ topsoil})^{*}\ 10^{-4})}{\rho b_{subsoil}} \text{ , (1)}$$

where T_{add} is the additional thickness of the sub-soil layer expressed in cm needed to reach the equivalent soil mass, $M_{soil\ equiv}$ is the equivalent soil mass of the denser horizon in kg. ha^{-1}. In our study, the dense 0-29 cm layer was the reference treatment in 2019 with a bulk density of 1.37 g.cm^{-3} giving an equivalent soil mass ($M_{soil\ equiv}$) of 3963 kg. ha^{-1}. $M_{soil\ topsoil}$ is the soil mass in the surface (tilled) layer and ρb sub-soil is the bulk density of the underlying 29-35 cm layer (in g.cm^{-3}). Carbon stocks per hectare in equivalent soil masses (Stock $_{C\ equiv}$) were calculated by adding the carbon stock in the surface layers (Stock $_{C\ topsoil}$) and in the additional underlying layers (Stock $_{C,\ Tadd}$) with the following formula:

$$\text{Stock}_{C\ equiv} = \text{Stock}_{C\ topsoil} + \text{Stock}_{C\ Tadd} \text{ , (2)}$$

At La Cage experiment, the soil sampling strategy was designed to calculate SOC stocks on an equivalent soil mass (ESM) basis Ellert and Bettany (1995) over a depth at least equal to the deepest tillage event. The ploughing depth was *ca*. 30 cm before 1998 and shallower afterwards, about 25 cm (Autret et al., 2016). The sample was taken at the depth equivalent to a soil mass of 4300 kg. ha^{-1}. The carbon stocks were calculated by multiplying the SOC contents with this equivalent soil mass.

We then calculated the additional carbon storage (ΔSOC stock) considering each time the conventional control at La Cage (CON-LC) and the conventional control at QualiAgro (CON-QA). The following formula was used:

$$\Delta\text{SOC stock} = \text{Stock}_{C\ Practice} - \text{Stock}_{C\ conventional} \text{ , (3)}$$

With Stock $_{C\ Practice}$: the carbon stock of the agroecological practice and Stock $_{C\ conventional}$: the carbon stock of the conventional control. The standard deviation used for the additional carbon stock was calculated based on the equation described by Kuzyakov and Bol, (2004) as follows:

$$SD_{\Delta SOC}\text{stock} = \sqrt{(SD_{stock\ C\ Practice})^2 + (SD_{stock\ C\ conventional})^2} \text{, (4)}$$

2.3 Particle size and density fractionation

The method uses a preliminary disaggregation aiming at the best compromise between maximum destruction of micro-aggregates of size < 50 µm, and respect of the integrity of organic debris (Balesdent et al., 1991) and combines fractionation by particle size to separate POM from OM associated with clays and silts minerals with water flotation to separate POM from sands. For this purpose, approximately 50 g of soil was suspended in 180 mL of 0.5% sodium hexametaphosphate (SHMP) saline solution in a 250

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mL polyethylene bottle; 10 glass beads were added and the whole set to agitation by inversion (REAX 2 type inversion mixers) for 16 hours, at a speed of approximately 50 rpm to destroy the aggregates. The SHMP solution and the glass beads allows to completely disperse soil aggregates > 50 µm diameter in these soils (Balesdent et al., 1991). After agitation, the suspension was first sieved on a 200 µm sieve from which the refusal, the coarse fraction, was recovered in a 250mL glass beaker. We separated the coarse POM (cPOM) from the coarse sands (cSand) by flotation in water. The suspension <200 µm in a second time was submitted to a second sieving at 50µm and the same operations were performed to separate the fine POM (fPOM) from the fine sands (fSand) using water flotation. The suspension <50 µm is submitted to ultrasounds by imposing an energy of 300 $J.mL^{-1}$ necessary to disperse the micro-aggregates (Balesdent et al., 1998). After this step, we sieved the suspension <50 µm to 20 µm to recover the coarse silts of size between 20 and 50µm (cSilt) remaining on the sieve. The suspensions containing particles <20 µm were pooled in a 2L beaker. The separation of the fine silts between 2 and 20µm (fSilt) from the clays was performed by centrifugation of the <20 µm filtrate at 64 g (circa 500 rpm) for 10min. The supernatant containing the clays was collected in a 5L beaker. The same process was repeated 4 to 5 times by resuspending the pellet for an optimal recovery of fine silts by decantation. The supernatant collected in the 5L beaker constitutes the clay fraction (<2 µm) and the pellet after repeated centrifugation constitutes the fine silt fraction. To reduce the volume of the clay suspension to be freeze-dried, we added $CaCl_2$ to flocculate the clay particles and by centrifugation for 20 min at 16000 g (circa 8000 rpm) we recovered the pellet which constitutes the clay fraction. An aliquot of the supernatant was taken to determine the dissolved organic carbon (DOC). The particle-size and density fractionation resulted in recovery rates of 95 ± 2% of the initial sample mass and 98 ± 6% recovery of carbon.

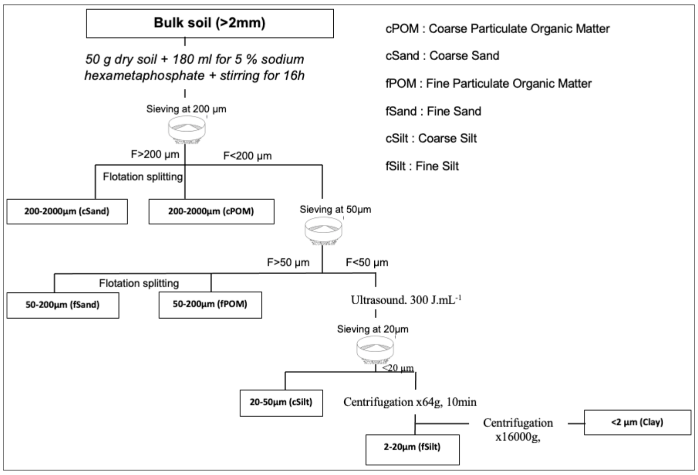

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Fig. 1 Particles size and density fractionation protocol (adapted from Balesdent et al., 1998). The POM fraction is the sum of the cPOM, fPOM, cSand and fSand fractions, while the MAOM fraction is the sum of the cSilt, fSilt and Clay fractions.

2.3.1 Fractions preparation and elemental analysis (C, N)

The fractions obtained during this fractionation were dried or freeze-dried. The organic (cPOM, fPOM) and mineral (cSand, fSand, cSilt) fractions were oven dried at 50°C for 3 days, while the fine silt (fSilt) and clay (Clay) fractions were freeze dried. Each fraction was weighed and C, N were determined using dry combustion (elemental analyzer, Elemantar Vario ISOTOP).

2.4 Rock-Eval® (RE) thermal analysis

We analyzed 28 samples of bulk soil, using a RE6 Turbo apparatus (Vinci Technologies). A small amount of soil (about 60 mg) was required for the analysis, which was performed in two consecutive steps, during which carbon-containing effluents were directly detected. First, the sample underwent pyrolysis in an inert atmosphere (N_2), followed by oxidation in the presence of O_2 (ambient air). The heating routine applied during pyrolysis was that proposed by Disnar et al. (2003) and Baudin et al. (2015), including a three-minute isotherm at 200 °C, followed by a 30 $°C \cdot min^{-1}$ heating ramp to 650 °C. Oxidation began with a one-minute isotherm at 300 °C, followed by a 20 $°C \cdot min^{-1}$ heating ramp to 850 °C and a final five-minute isotherm at 850 °C (oxidation routine presented in Baudin et al. (2015) as the "bulk rock/basic" method). Simultaneous detection of effluents during both analytical steps generated a total of five thermograms per sample describing the evolution of hydrocarbons during pyrolysis (HC_PYR), and CO and CO_2 during both pyrolysis and oxidation steps (CO_PYR, CO_2_PYR, CO_OX, CO_2_OX).

2.4.1 Rock-Eval® parameters

The classical Rock-Eval® parameters were acquired using the RockSix software (Vinci Technologies) with a good reproducibility (Pacini et al., 2023). They include: six automatically generated "peaks" defined as specific areas of the three pyrolysis thermograms (S1, S2, S3, S3', S3CO and S3'CO; Lafargue et al. (2018)), the amount of pyrolyzed carbon (PC corresponding to the sum of organic C released as HC, CO, and CO_2 during pyrolysis), total organic carbon (TOC corresponding to the amount of organic C released during analysis), inorganic carbon (MinC corresponding to the amount of C released from carbonate cracking), hydrogen index (HI corresponding to the ratio of hydrocarbons released to TOC), and oxygen index (OI_{RE6} corresponding to the ratio of organic oxygen released to TOC). In addition, other parameters used as predictors by the PARTYSOCv2.0EU model were

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calculated based on thermograms obtained using R scripts available on Zenodo (https://zenodo.org/record/4446138#.YDe84Xlw2SQ) (Cécillon et al., 2021, Kanari et al., 2021). These include: PseudoS1 (the sum of carbon released during the first 200 s of isothermal 200°C pyrolysis as HC, CO, and CO_2), the S2/PC ratio (the ratio of the amount of hydrocarbons released excluding the first 200 s of pyrolysis to the pyrolyzed carbon), the PC/TOC ratio, the HI/OIRE6 ratio, and ten temperature parameters (e.g., T30, T50, T70, T90) that describe the evolutionary steps, i.e., at what temperature 30, 50, 70, and 90% of a given gas was released. A detailed description of the definition, units, and equations used to calculate all parameters can be found in the study of Kanari et al. (2021). The HI and OIRE6 are commonly reported indices that represent proxies of the SOM H/C and O/C ratios respectively.

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2.4.2 PARTY$_{SOC}$ model based on Rock-Eval® (RE)

In this study, we used the random forest model based on RE results PARTY$_{SOCv2.0EU}$ (https://zenodo.org/record/4446138#.YDe84Xlw2SQ) proposed by Cécillon et al. (2021). This model was calibrated on data from 6 long-term agricultural experiments including a bare fallow treatment in northwestern Europe and can predict the proportion of persistent SOC at a centennial timescale in topsoil samples (0-30 cm). The model requires a set of 18 RE parameters (e.g., Kanari et al., 2021) characteristic of a sample and provides a prediction of the proportion of stable SOC for soils from the La Cage and the QualiAgro long-term experiments. The 18 RE parameters retained were the RE temperature parameters T70HC_PYR, T90HC_PYR, T30CO_2_PYR, T50CO_2_PYR, T70CO_2_PYR, T90CO_2_PYR, T70CO_OX, T50CO_2_OX, T70CO_2_OX, and T90CO_2_OX and the RE parameters PseudoS1, S2, S2 / PC, HI, HI / OI_{RE6}, PC, PC / TOC_{RE6}, and TOC_{RE6} (Cécillon et al., 2021).

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2.5 Long-term incubation

Polyvinyl chloride (PVC) cylinders 5.7 cm in diameter and 4 cm in height with 2 mm perforations were used to build soil microcosms. A 50 µm mesh fabric at the bottom of the cylinder supported the soil while promoting gas exchange. Each cylinder was weighed empty and then with fresh soil equivalent to 100 g of dry soil. The soil samples were then brought to a bulk density of 1.3 g.cm^{-3} with a hand press and mold. Knowing the initial water content, the samples were gradually brought to pF 2.5 by adding water with a Pasteur pipette. Then, the microcosms were mounted in 0.5 L jars. The soil cylinders were placed on PVC racks and 15 mL of water was added to the bottom of the jars to stabilize the humidity. The jars were sealed and the whole set was placed in the incubator at 20°C for one week pre-incubation. Four replicates per agricultural practice were prepared.

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After the pre-incubation period, we readjusted the water content of the soil cylinders to pF 2.5 when necessary. A total of 28 soil cylinders were incubated for 484 days under the same temperature (20°C) and moisture (pF2.5) conditions.

- ***Mineralization measurement***

Soil organic carbon (SOC) mineralization in samples from both long-term experiments (LTEs) was measured nondestructively using a micro gas chromatograph (μGC 490; Agilent Technologie; USA). Measurements were performed 1, 3, 7, 14, 28, 35 days, then one measurement every 2 weeks until the sixth month and finally, one measurement every month until the end of incubation. The CO_2 emitted is measured in parts per million (ppm). It is then converted to μg C-CO_2 g^{-1} of dry soil using the following formula: $\mu g\ C - CO_2 . g^{-1}\ \text{dry soil} = \frac{CO_2(ppm) * M_c * V_b}{V_M * M_{soil}}$ (5), (Védère et al., 2020).

With CO_2 (ppm): amount of CO_2 emitted measured by gas phase microchromatograph; Mc: molar mass of carbon in $g.mol^{-1}$; V_b: volume of the jar in L; V_M: molar volume of the gas in $L.mol^{-1}$ and M_{soil}: mass of the incubated dry soil in g. The absolute amount of carbon mineralized was expressed per unit of SOC to obtain the specific SOC mineralization in μg C–CO_2/100 μg SOC, i.e., % SOC mineralized (Kpemoua et al., 2023). To calculate the amount of additional carbon mineralized over the 484 days, we first calculated the difference in absolute carbon mineralization between the agroecological practice and the conventional control. We assume that the extra absolute carbon mineralized in the agroecological practice relative to the conventional control comes from the additional carbon. Given the amount of additional carbon (ΔSOC), we then expressed this extra absolute carbon mineralization in terms of additional carbon (%ΔSOC).

2.6 statistical analysis

All data were tested for normality and homogeneity of variance. Log-transformation was applied to the data for the cSand and fSand fractions, as the transformation improved the normality and variance substantially. A one-way ANOVA was used to detect significant differences at the 5% threshold in bulk soil carbon stocks, fractions, carbon pools and amount of carbon mineralized (Cmin). Once a significant difference was detected, Tukey's multiple comparison test was used to compare carbon stocks, additional carbon stocks, percentage of total carbon storage and percentage of additional carbon storage in either bulk soil, fractions and carbon pools according to agricultural practices. All statistical analyses were completed in R (version 4.0.2).

3 Results

3.1 SOC stocks

The application of organic wastes products (OWPs), increased soil organic carbon (SOC) contents in soils by 64% in biowaste composts treatment (BIOW), 40% in farmyard manure treatment (FYM) and 39% in residual solid waste compost treatment (MSW) compared to the conventional control (CON-

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QA); while, at La Cage, the implementation of organic agriculture (ORG) and conservation agriculture (CA) increased SOC contents by 6% and 35% respectively, relative to conventional control (CON-LC) (Table 1). The OWPs application significantly increased carbon stocks at QualiAgro. The SOC stocks were in the order: BIOW > FYM ≥ MSW > CON-QA (Table. 1). At La Cage, SOC stocks were in this order: CA > ORG ≥ CON-LC (Table 1).

3.2 SOC distribution in fractions

The mass proportion, carbon content and % carbon distribution of the physical fractions after particle size and density fractionation are presented in the supplementary data Table. S1 and Table. S2. The distribution of SOC stocks over the fractions obtained, expressed in t C. ha^{-1}, is given in Figs. 2a and 2b. Carbon distribution in conventional controls (CON-LC and CON-QA) showed that 19-22% of carbon was found in POM fractions, versus 78-81% in MAOM fractions (Figs. 4a and 4b). Overall, most of the organic carbon was located in the clay fraction (64 -72% SOC, see Table. S1 and S2) regardless of site and the agricultural practice implemented. The carbon distribution in QualiAgro indicated a significant increase of SOC stocks in the cSand, fPOM, cSilt and Clay fractions after OWPs application ($p<0.05$), while no significant difference was observed in the cPOM, fSand and fSilt fractions ($p>0.05$). In La Cage, the implementation of conservation agriculture significantly increased SOC stocks as fPOM and Clay fractions compared to organic and conventional agriculture which remained statistically equal.

We calculated the distribution of additional carbon (ΔSOC) in the fractions by difference of the carbon stock of the bulk soil or physical fractions under agroecological practices with the carbon stock of the bulk soil or physical fractions under conventional control (CON-QA or CON-LC respectively for the QualiAgro and the La Cage experiments). The additional carbon stock at QualiAgro was 23.86 ± 1.79 t C. ha^{-1} in BIOW compared to 15.46 ± 1.43 t C. ha^{-1} in FYM and 14.72 ± 1.28 t C. ha^{-1} in MSW (Fig. 2c). At La Cage, the additional SOC stock was 14.95 ± 2.49 t C. ha^{-1} in CA compared to 2.44 ± 1.38 t C. ha^{-1} in ORG (Fig. 2d). In terms of percentage, we observed that the coarse mineral fractions (cSand and fsand) have a negligible proportion of additional carbon at La Cage, representing 1% in CA and 0% in ORG, while this proportion was raised to 2% in FYM, 5% in MSW and 7% in BIOW at QualiAgro. This non-negligible proportion of carbon in the sand at QualiAgro suggests that not all particulate organic matter (POM-C) has probably been isolated from the sand. Hence, in the following, to define the POM-C fraction class, we combine the fractions of cPOM, fPOM, cSand and fSand together. Thus, we observed in the QualiAgro experiment that, 60-66% of the additional carbon was localized in mineral-associated organic matter fractions (MAOM-C), which included the cSilt, fSilt, and Clay fractions, versus 34-40% in POM-C; whereas, in La Cage experiment, 77-84% of the additional SOC stock was located in the MAOM-C versus 16-23% in the POM-C. Furthermore, among practices with equivalent additional carbon stocks (MSW, FYM, CA), OWPs application resulted in a higher proportion of additional carbon in POM-C (MSW: 34%; FYM: 40%) compared to CA (16%).

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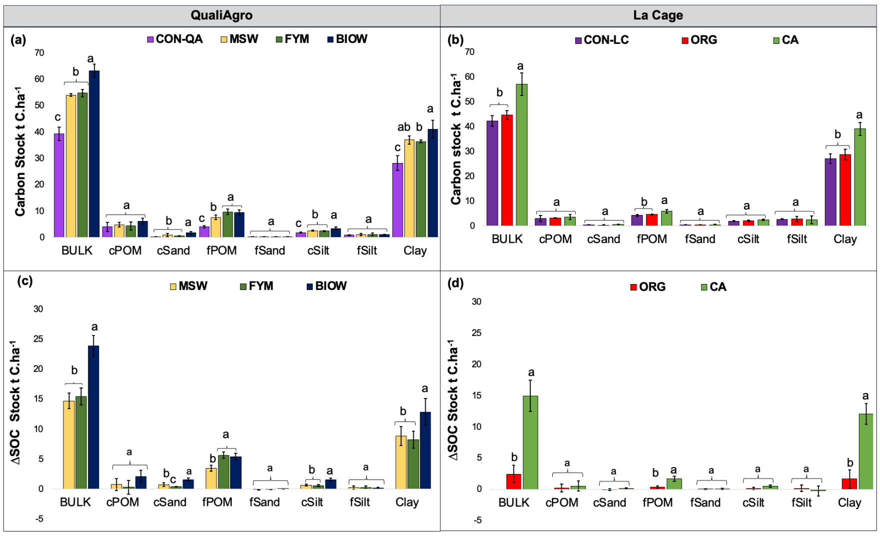
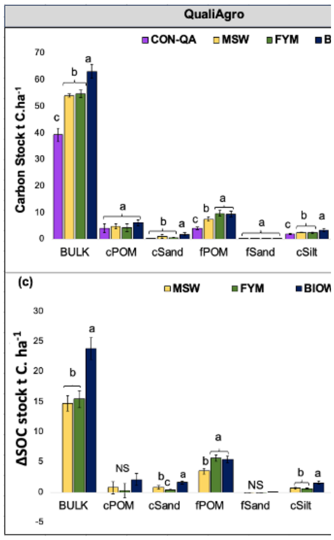


Fig. 2 Soil organic carbon stock and additional carbon (ΔSOC**)** stock of bulk soils and physical fractions (n = 4) at QualiAgro and La Cage experiments. The error bars represent the standard deviations. Grouped bars with different letters are significantly different between agricultural practices (Tukey-HSD, $p < 0.05$). CON-QA: conventional agriculture without organic inputs, BIOW: biowaste compost, MSW: municipal solid waste compost, FYM: farmyard manure, CON-LC: conventional agriculture, CA: conservation agriculture and ORG: organic agriculture. The POM fraction is the sum of the cPOM, fPOM, cSand and fSand fractions, while the MAOM fraction is the sum of the cSilt, fSilt and Clay fractions.

3.3 Estimating stable and active SOC pools with the PARTY$_{SOC}$ model

The PARTY$_{SOC}$ machine learning model was used to estimate the proportion of stable SOC under the different managements. The distribution of organic carbon stocks in the active and stable pools are shown in Fig. 3. In conventional controls, 38-43% of the soil carbon is found in the active pool, versus 57-62% in the stable pool. The organic wastes products (OWPs) application significantly increased the size of the active pool relative to conventional control (Fig. 3a, ANOVA, $p<0.05$). It was of 31.87 ± 2.23 t C. ha^{-1} in BIOW compared to 29.62 ± 1.97 t C. ha^{-1} in FYM, 26.97 ± 1.07 t C. ha^{-1} in MSW and 16.76 ± 1.69 t C. ha^{-1} in CON-QA. The OWPs application significantly increased the size of the stable SOC pool in the BIOW (31.29 ± 0.91 t C. ha^{-1}) and MSW (25.15 ± 1.36 t C. ha^{-1}) treatments compared to the FYM (25.15 ± 1.44 t C. ha^{-1}) and CON-QA (22.55 ± 1.31 t C. ha^{-1}) which were statistically similar. Contrastingly, at La Cage experiment, 20 years of contrasted management had no significant effect on



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the size of the stable SOC pool (28.02 ± 2.95 t C. ha^{-1}, 26.31 ± 0.93 t C. ha^{-1}, and 26.08 ± 1.89 t C. ha^{-1} for CA, ORG, and CON-LC respectively). However, CA significantly increased the size of the active pool (29.15 ± 5.79 t C. ha^{-1}) compared to ORG and CON-LC in which it was similar (18.35 ± 3.47 t C. ha^{-1} and 16.14 ± 0.97 t C. ha^{-1} respectively) (Fig. 3b).

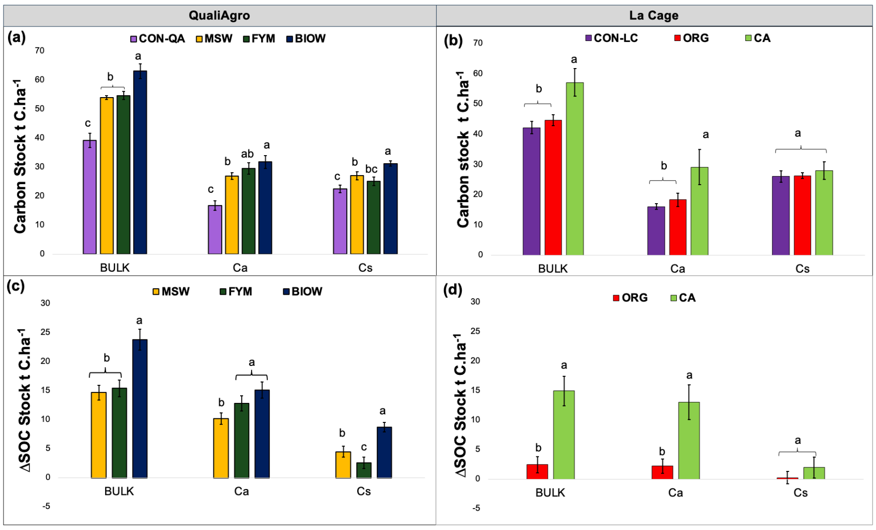

Fig. 3 Soil organic carbon stock and additional carbon (ΔSOC**)** stock of bulk soils, active carbon (Ca) and stable carbon (Cs) (n = 4) at QualiAgro and La Cage experiments. The error bars represent the standard deviations. Grouped bars with different letters are significantly different between agricultural practices (Tukey-HSD, $p < 0.05$). CON-QA: conventional agriculture without organic inputs, BIOW: biowaste compost, MSW: municipal solid waste compost, FYM: farmyard manure, CON-LC: conventional agriculture, CA: conservation agriculture and ORG: organic agriculture.

The results of additional carbon (i.e., the difference between the active or stable carbon pool of agroecological practices and the active or stable carbon pool of conventional control) distribution in the active and stable carbon pools are shown in Figs. 3c and 3d. In the QualiAgro experiment, BIOW (15.85 ± 1.48 t C. ha^{-1}) and FYM (13.36 ± 1.16 t C. ha^{-1}) had similar active carbon pool size, higher than in the MSW (12.34 ± 0.75 t C. ha^{-1}). This active pool, represented 63-83 % of the additional carbon storage (Fig. 4c). Additional stable carbon pools ordered as follows: BIOW (8.74 ± 0.79 t C. ha^{-1}) > MSW (4.51 ± 0.94 t C. ha^{-1}) > FYM (2.60 ± 0.97 t C. ha^{-1}) and represented between 17% (FYM) to 37% (BIOW) of

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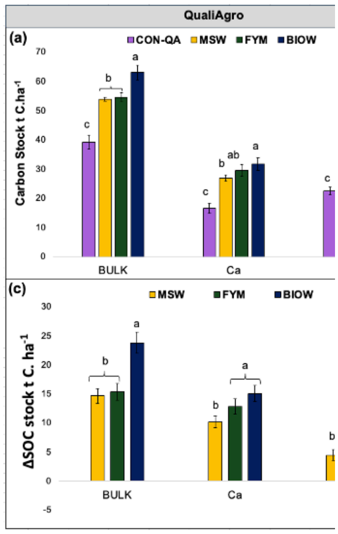

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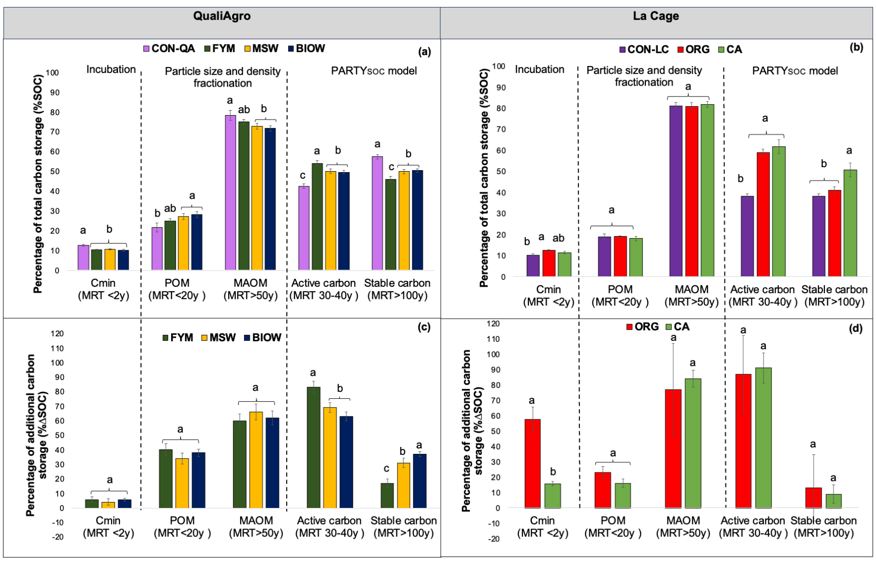
the additional carbon. At La Cage, 87% (CA) to 91% (ORG) of the additional carbon was in the active pool versus 9% (ORG) to 13% (CA) in the stable pool (Fig. 4d).

3.4 Carbon mineralization kinetics

At the end of soil incubation (day 484), the cumulative amounts of mineralized carbon expressed as percent soil organic carbon (%SOC) at La Cage experiment, differed significantly between the 3 cropping systems, i.e., 12.60 ± 0.29 %SOC in ORG versus 11.52 ± 1.19 %SOC in CA and 10.21 ± 1.36 %SOC in CON-LC (Fig. 4b). In the QualiAgro experiment, the specific carbon mineralization kinetics were significantly higher on the conventional control (CON-QA) without organic inputs compared to the soils receiving OWPs, where the mineralization carbon of the MSW and FYM plots were statistically identical but higher than the BIOW plot (Fig. 4a).

Overall, these two experiments show opposite trends. On the one hand, higher carbon mineralization under agroecological practices (ORG and CA) in La Cage experiment relative to the conventional control (CON-LC), and on the other hand, lower carbon mineralization under agroecological practices (MSW, FYM and BIOW) in QualiAgro experiment relative to the conventional control (CON-QA). Moreover, the percentage of additional carbon mineralized (%ΔSOC) at La Cage in CA (15% of ΔSOC) and ORG (57% of ΔSOC) was higher than at QualiAgro (4-5% of ΔSOC) (Figs. 4c and 4d). It must be noted however that the additional carbon stock was very small in the ORG treatment, which numerically explains the high %ΔSOC calculated value.



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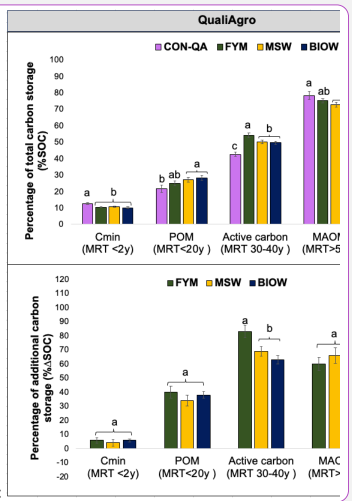

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Fig. 4. Distribution of total carbon and additional carbon in carbon kinetic pools [Cmin (carbon mineralized), Active and Stable carbon] or fractions [POM and MAOM] under agricultural practices. The error bars represent the standard errors. Grouped bars with different letters are significantly different between agricultural practices (Tukey-HSD, $p < 0.05$).

4 Discussion

4.1 Both POM-C and MAOM-C are sensitive to management

The observed distribution of SOC in the fractions, i.e., most of the SOC (70-80%) being located in the fine fraction (<50 µm), regardless of the agricultural practice implemented (Figs. 4a and 4b), is in agreement with the literature (Christensen, 1985;1987; Balesdent, 1996; Baldock and Skjemstad, 2000; Jolivet et al., 2003; Carter et al., 2003; Beare et al., 2014, Curtin et al., 2016, Poeplau et al., 2018).

Many studies have indicated that the POM-C fraction is more sensitive to land use and management changes than the MAOM-C fraction (Cambardella and Elliot, 1992, Elliot et al., 1994, Bayer et al., 2001, Salvo et al., 2010). However, our study showed that both POM-C and MAOM-C fractions were both highly sensitive to the implementation of agroecological practices ca. 20 years. The application of OWPs resulted in additional soil organic carbon both as POM-C (34-40% of ΔSOC) and MAOM-C (60-66% of ΔSOC), while conservation and organic agriculture resulted in additional organic carbon mainly as MAOM-C (77-84% of ΔSOC) and less as POM-C (16-23% of ΔSOC). A significant proportion of the additional carbon is associated with soil minerals, particularly in the clay fraction (See Table. S1 and Table. S2).

Studies comparing no-tillage versus conventional tillage management showed in the surface layer an increase in the POM-C fraction with no-tillage and no difference in MAOM-C (Wander et al., 1998, Hussain et al., 1999; Carbonell-Bojollo et al., 2015; Samson et al., 2020). A recent meta-analysis by Prairie et al. (2023) indicated that no-tillage increased both POM-C and MAOM-C fractions in soils when this practice was maintained up to 6 years. However, the increase in the MAOM-C fraction was less important than that of the POM-C fraction. We therefore ascribe the observed increase of MAOM-C at La Cage to the no-tillage and the introduction of cover crops and the diversification of species (e.g., legumes) in the rotation. Interestingly, an earlier analysis of SOC distribution at La Cage, after 5 years of differentiation, showed a significant increase of POM-C in the conservation agriculture system, while no change of POM-C in the organic system and no significant change of the MAOM-C (Balabane et al., 2005), suggesting either that it took more than 5 years for the additional POM-C to be broken down and biodegraded as MAOM-C, or that the introduction of alfalfa as the cover crop instead of fescue since 2008 (i.e., 12 years later) resulted in more direct rhizodeposits inputs to MAOM-C. Indeed, according to Autret et al. (2016), the estimated inputs from fescue were lower (0.88 t C. ha^{-1}. yr^{-1}) than those coming from alfalfa as a cover crop (1.12 t C. ha^{-1}. yr^{-1}), about half of these amounts deriving from root

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material. The cover crops and legume rotation in conservation agriculture and the legume rotations in organic agriculture would likely have affected carbon input via the root system as dead roots (POM) and rhizodeposits (MAOM). This would explain the high proportion of carbon associated with MAOM-C. Typically, the cover crops characterized by low litter quality (e.g., grass) resulted in higher accumulation of POM that was abundant in plant carbon, while cover crops with high litter quality (e.g., legumes) contributed to higher accumulation of SOC (Cotrufo et al., 2013), and of microbial necromass carbon (Zhang et al., 2022) in MAOM-C. Thus, the high proportion of carbon in the MAOM-C at La Cage (77-84% of ΔSOC) compared to QualiAgro (60-66% of ΔSOC) could be explained by the type and quality of the carbon input. Because, the cover crops increase the time period in which plant roots interact with the soil environment (Tiemann et al., 2015), they deliver an additional source of root litter and exudates, providing greater diversity in belowground inputs (Austin et al., 2017). This promotes the microbial growth and turnover in rhizosphere hotspots, processes that can enhance the formation of MAOM (Kallenbach et al., 2016).

The recent meta-analysis, conducted by Zhang et al. (2022), indicated that the application of OWPs significantly increases both MAOM and POM fractions in the soil relative to the control treatment, which is consistent with our results. Peltre (2010) observed that the short-term application (4 times) of the OWPs at QualiAgro increased the additional carbon only in the POM-C fraction, the MAOM-C fraction <50µm being unchanged. Paesch et al. (2016) later found that 7 successive applications of the OWPs led to additional carbon in occluded small POM (< 20µm) and in the fine silt + clay fraction (< 6.3 µm). After 11 applications of OWPs we observed an increase in fine POM (50-200µm), coarse silt (20-50µm) and MAOM-C (<50 µm). This series of results indicate that the application of the OWPs increase in the short term the POM-C fraction and that in a longer term (> 10 years) the organic carbon in the POM-C is transferred to the MAOM-C through biological activity in the soil. The transfer of additional carbon from POM to MAOM is however slower at QualiAgro compared to La Cage. Cotrufo et al. (2015), shows that POM and MAOM likely form under different biochemical and physical pathways. While there is certainly some transfer from POM to MAOM, much of MAOM formation occurs from dissolve organic matter (DOM) early during decomposition. There might just be a great abundance of DOM and labile inputs int La Cage to explain greater MAOM formation.

4.2 POM heterogeneity can hamper SOC stability assessments

The POM in this study consists of crop residues and/or added manure or composts and microbial residues. The agroecological practices with equivalent additional carbon stocks (MSW, FYM, CA) showed after 20 years a higher proportion of additional carbon in POM-C under MSW (40% of ΔSOC) and FYM (34% of ΔSOC) compared to CA (16% of ΔSOC). These results show that it is likely that different management (e.g., OWPs application, no-tillage, cover crops and legume) alter the way gross

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organic carbon inputs were distributed among the different organic carbon fractions. These results can be explained by the fact that the decomposition rate of organic amendments and the SOC formed and remaining in the long term vary according to the intrinsic quality of the amendment (Lashermes et al., 2009). For example, Paustian et al. (1992) observed that high lignin content of FYM, which was more recalcitrant to decomposition, resulted in greater accumulation of C than lower lignin amendments, such as straw. Previous studies demonstrated that the OWPs generally are partially stabilized by the composting and storage processes (Benbi and Khosa, 2014), unlike plant biomass, which is fresh OM.

The incubations revealed that in La Cage experiment, a higher percentage of the additional carbon was mineralized in conservation agriculture (15% of ΔSOC) over 484 days than additional carbon at QualiAgro (4-5% of ΔSOC) (Figs. 4c and 4d). The low additional carbon mineralization at QualiAgro raises questions about the degradability of POM derived from OWPs, which were in higher proportion (34-40% of ΔSOC) than at La Cage experiment (16-23% of ΔSOC). It is therefore likely that the OWPs-derived POM were more recalcitrant with higher mean residence times compared to plant-derived POM. The mean residence time of < 20 years given to POM in the study by Balesdent, (1996) may not be applicable to systems where pre-processed exogenous OM are applied, because in the formed is based on situations where organic input were crop residues. Thus, we assume a greater chemical recalcitrance of POM-C in plots receiving OWPs, thereby reducing decomposers activity and carbon transfer to the fine soil fraction (<50 µm).

4.3 Different methods provide a contrasted evaluation of biogeochemical stability

We used different methods to assess the biogeochemical stability of the additional carbon stored in soil thanks to specific management options. The incubation method isolates carbon with mean residence time (MRT) ranging from days to years (MRT < 2y in this case), while particle size and density fractionation isolate carbon fractions ranging from years to decades (POM with MRT < 20y and MAOM with MRT > 50y) and $PARTY_{SOC}$ model based to RE thermal analysis that isolate carbon pools ranging from decades to centuries (Active pool with MRT ~30-40y and Stable pool with MRT > 100y).

In the QualiAgro experiment, the incubations results indicate greater stability of additional carbon compared to bulk SOC in the conventional control (i.e., lower specific carbon mineralization for soils receiving OWPs relative to CON-QA). However, the results of particle size and density fractionation and $PARTY_{SOC}$ based to RE thermal analysis indicate that the additional carbon stored by OWPs application is on average less stable than the soil carbon in the conventional control (CON-QA). This is because, in these plots the additional carbon has a higher proportion of POM (MRT < 20y) and Active carbon (MRT ~ 30-40y) than the conventional control (Figs. 4a and 4c). As the incubations target carbon

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with MRT of the order of incubation length (i.e., MRT <2y in this study), we posit that this difference is due to the fact that the different methods do not target the carbon pools with the same MRT. Put together, these results suggest that, on the scale of a few decades, soil additional carbon in QualiAgro experiment is less stable than soil carbon in conventional control, but in a shorter term (i.e., MRT < 2y), the additional carbon is quite resistant.

In La Cage experiment, the results of the incubations and the PARTY$_{SOC}$ model based to RE thermal analysis are consistent and indicate that the additional carbon stored by conservation agriculture and organic agriculture is less stable than the soil carbon in the conventional control (CON-LC), whereas the particle size and density fractionation indicates a more stable additional carbon, i.e., a higher proportion of MAOM (MRT > 50 years) than the conventional control (Fig. 4). However, the study by von Lützow et al. (2006) showed that MAOM does not have a unique mean residence time. For example, land-use change (native and cropped lands) studies have indicated a decrease in carbon content in MAOM-C over time (Balesdent et al., 1998, Yeasmin et al., 2019). Lutfalla et al. (2019), using samples from 42 plots in Versailles, observed a decrease in carbon content in the clay fraction (< 2 µm) after 52 years of bare fallow conditions, thus questioning the long-term persistence of carbon associated with clays and MAOM-C. Our results provide evidence that at least part of the carbon contained in MAOM may not persist in soils over the long term as shown by others previously (e.g., Balesdent, 1987, Keiluweit et al., 2015, Lutfalla et al., 2019, Chassé et al., 2021). We therefore hypothesize that the additional carbon stored in the form of MAOM has a lower MRT than the MAOM in conventional control.

Based on these results, our hypothesis that the biogeochemical stability of additional carbon is less stable than the carbon in the conventional control is not always verified. However, considering that MAOM is kinetically heterogeneous, then the results of these methods can be reconciled. So, the additional carbon is overall less stable at a decadal or pluri-decadal timescale than the carbon stored in the conventional control in both long-term experiments. Furthermore, taking all these elements and the complementary nature of the methods into consideration, it emerges that the additional carbon stored thanks to OWPs application is more stable in the short (MRT < 2y) and long term (MRT > 100y) than the additional carbon enabled by alternative cropping systems, but less in the decadal and pluridecadal time scale. The large time scale of SOM persistence shows that qualifying SOC simply as stable or labile is not sufficient. It is essential to always associate a temporality with the biogeochemical stability that is described in order to better assess the persistence of carbon in soils.

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5 Conclusion

This study provided detailed information on the biogeochemical stability of additional carbon via a multi-methods evaluation. Soils from the same experimental sites but under widely contrasting management have resulted in contrasting carbon contents and stocks ca. 20 years of management. The results of particle size and density fractionation and $PARTY_{SOC}$ model suggests that the additional carbon contained in MAOM may not persist in soils over the long term (> 50 years). Incubation, on the other hand, provided information on the short-term stability of additional carbon (i.e., MRT <2 years). Overall, the multi-methods evaluation showed that additional carbon was less stable at the decadal and pluri-decadal time-scales than carbon under conventional controls. However, incubations and $PARTY_{SOC}$ model based to RE thermal analysis revealed that additional SOC in the QualiAgro experiment was more stable in short- term (MRT < 2y) and long- term (MRT >100y) than that in La Cage experiment. Additional SOC deriving from organic wastes, i.e., biomass that has been partially decomposed and transformed through its processing (digestion by cattle, storage and composting) prior to its incorporation in soil, would have a different biogeochemical stability than that deriving directly from plant biomass. Widely used (incubation, particle size fractionation) and increasingly used methods (RE) provide seemingly inconsistent assessments of the biogeochemical stability of SOC. These apparent contradictions can be explained by the fact that they address different kinetic pools of organic carbon. Care must be taken to specify which range of residence times are considered when using any method intending to evaluate the biogeochemical stability of SOM, as well as when using the terms stable or labile. As we found that the additional SOC stored thanks to the implementation of different management options had contrasted biogeochemical stabilities, there is a need to evaluate the biogeochemical stability of the additional SOC stored via other management options (e.g., agroforestry, lengthening temporary leys, no tillage…).

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Author contribution

TPIK, CC, PB and SH designed the study. TPIK performed soil fractionation and long-term incubation. FB and CP performed the RE6 thermal analyses and elementary analyses respectively. PB performed the R codes to PARTY$_{SOC}$ machine learning model. TPIK wrote the R codes and performed all statistical analyses. TPIK, CC, PB, SH and FB contributed to the interpretation of the results. TPIK prepared the paper with contributions from all coauthors.

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Droite : 0,63 cm

Page 22 : [2] Modifier Unknown

Code de champ modifié

Page 22 : [3] a mis en forme Israël Kpemoua 27/02/2024 12:11:00

Français

Page 22 : [4] a mis en forme Israël Kpemoua 27/02/2024 12:11:00

Français

Page 22 : [5] a mis en forme Israël Kpemoua 27/02/2024 12:11:00

Anglais (E.U.)

Page 22 : [6] Modifier Unknown

Code de champ modifié

Page 22 : [7] a mis en forme Israël Kpemoua 27/02/2024 12:12:00

Français

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Français

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Anglais (E.U.)

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Code de champ modifié

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Français

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Français

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Anglais (E.U.)

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Anglais (E.U.)

Page 1 : [22] a mis en forme **Claire Chenu** **29/04/2024 15:10:00**

Droite : 0,63 cm

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Anglais (E.U.)

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Français

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Français

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Anglais (E.U.)

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Anglais (E.U.)

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Anglais (E.U.)

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Français

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Français

Page 26 : [35] a mis en forme **Israël Kpemoua** **27/02/2024 13:36:00**

Français

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Français

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Français

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Français

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Français

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Anglais (E.U.)

Page 26 : [43] Modifier Unknown

Code de champ modifié

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