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Are carbon-storing soils more sensitive to climate change? A laboratory evaluation for agricultural temperate soils

Tchodjowiè P. I. Kpemoua[1,3], Sarah Leclerc[1], Pierre Barré[2], Sabine Houot[1], Valérie Pouteau[1], Cédric Plessis[1], Claire Chenu[1]

[1] UMR Ecosys, Université Paris-Saclay, INRAE, AgroParisTech, Palaiseau, 91120, France

[2] Laboratoire de Géologie, UMR 8538, Ecole Normale Supérieure, PSL Research University, CNRS, Paris 75005, France

[3] Agence de la Transition Écologique, ADEME, 49004 Angers, France

Corresponding author:

E-mail address: claire.chenu@inrae.fr (C. Chenu)

Highlights

- Soil moisture regime and temperature significantly affect the carbon mineralization
- Dry wet cycles did not stimulate the carbon mineralization relative to wet controls
- Specific carbon mineralization did not differ among the three cropping systems at La Cage
- Lower specific carbon mineralization in soils receiving organic waste products at QualiAgro
- Carbon-storing soils have a similar sensitivity to climate events as baseline soils

Abstract

A range of agroecological practices allow to increase soil organic carbon (SOC) stocks, which makes a positive impact on climate change mitigation and soil health, but the permanence of this additional SOC storage can be questioned, in particular in a climate change context. Increased temperatures, accentuated evaporation of terrestrial water and increased atmosphere moisture content are anticipated, resulting in more frequent droughts and heavy precipitation events. Understanding the SOC dynamics and assessing the sensitivity of carbon mineralization to these climatic events is necessary to anticipate future carbon losses in terrestrial ecosystems. To this respect, it seems relevant to investigate carbon-storing soils as increased carbon mineralization induced by climate change may limit the carbon storing potential in agricultural soils. Thus, we evaluated the sensitivity of SOC mineralization to increased temperature, decreased soil moisture and drying-rewetting cycles using soils from long-term field experiments. We performed an incubation experiment on topsoil (0-30cm) samples from temperate luvisols that had been under 20 years under conservation agriculture (CA), organic agriculture (ORG) and conventional agriculture (CON-LC) at the La Cage experiment, and under organic waste 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). Soil samples were incubated in the lab for 3 months under different temperature conditions (20, 28 and 35°C) or under different moisture conditions (matric potential: pF1.5; pF 2.5 and pF 4.2) or under several dry (pF 4.2)-wet (pF 1.5) cycles (DWC). The results shown that, whatever the agricultural practices, soil moisture regime and temperature significantly affect the SOC mineralization. Overall, the DWC did not stimulate soil carbon mineralization relative to wet controls (pF1.5 and pF2.5). Whatever the soil moisture regime and temperature, specific carbon mineralization was similar between agricultural practices at La Cage, while at QualiAgro, specific carbon mineralization was lower in soils receiving organic waste products (OWPs) compared to the

baseline soil. These results suggest a strong carbon stabilization by OWPs in soils as assessed by laboratory incubation experiments. Within each long-term experiment, we observed no significant difference between the carbon-storing soils (CA, ORG, MSW, FYM and BIOW) and their respective baseline soils (CON-LC and CON-QA) in the delta SOC mineralized whatever the soil moisture regime. The Q_{10} also indicated no significant difference between carbon-storing soils and their respective baseline soils. These results indicate that the SOC mineralization in carbon-storing soils had a similar sensitivity to the soil moisture regime and temperature as the baseline ones. Hence, the implementation of these agroecological practices appears beneficial for climate change mitigation, even in the context of extreme climatic events.

Keywords: Carbon mineralization; agroecological practices; organic waste products; climate change; sensitivity

1. Introduction

The 4p1000 initiative encourages the establishment of agricultural practices that increase and/or preserve soil carbon stocks (www.4p1000.org). At the field scale, changes in soil organic carbon (SOC) stocks result from an imbalance between carbon inputs (crop residues, litterfall, root exudates, exogeneous organic matter application, etc.) and carbon outputs due to SOC mineralization, leaching or erosion (Lal, 2018). It is generally agreed that the most efficient way to increase SOC stocks is to increase carbon inputs (e.g., Virto et al., 2012, Autret et al., 2016, Fujisaki et al., 2018). This can be achieved by increasing field biomass production and residue return (e.g., cover crops, Poeplau & Don, 2015; Autret et al., 2016), or by mobilizing and spreading external carbon resources such as organic waste products (OWPs) (Peltre et al., 2012, Paetsch et al., 2016). The implementation of agroecological practices that increase carbon inputs and/or reduce carbon outputs (e.g., conservation agriculture, organic agriculture, OWPs application) generally result to additional carbon storage (Peltre et al., 2012, Autret et al., 2016, Paetsch et al., 2016, Pellerin et al., 2019); such soils are referred to "carbon storing soils" in this study. However, the question is whether the adoption of these agroecological practices would still be beneficial for carbon sequestration in a warmer, drier, wetter climate or with intense dry-wet cycles?

It is widely recognized that climate change affects carbon mineralization in soils (Joly et al., 2023). Climate change is leading to an overall temperature increase, as well as increases in the frequency and intensity of extreme climatic events such as droughts, heavy precipitation, fires, or freeze-thaw cycles (Shukla et al., 2019). There is also an increase in the evaporation of terrestrial water and an increase in the moisture level in the atmosphere, leading to frequent cycles of drought and heavy rainfall events (Dai, 2013, Donat et al., 2016). Overall, these climatic events could have positive or negative impacts on CO_2 emissions into the atmosphere by affecting ecological processes which control the dynamics of organic carbon in agricultural soils. The existence of this important feedback effect has prompted several studies of how climate change affects the kinetics of SOC mineralization and the emission of CO_2 from soils (Kirschbaum, 2000, Smith et al., 2008). For example, increased soil temperature is known to accelerate SOC decomposition because temperature-dependent reactions performed by microorganisms (Davidson and Janssens, 2006) result in more rapid CO_2 emissions from soil to the atmosphere (Trumbore and Czimczik, 2008, Karhu et al., 2014). Soil moisture can have a great impact on SOC decomposition by affecting the oxygen diffusion into the soil and the substrate availability for soil microorganisms (Linn and Doran, 1984; Suseela et al., 2012, Moyano et al., 2013, Wang et al., 2014, Zhou et al., 2014, Sierra et al., 2015). With climate change, it is expected that dry-wet cycles will increasingly occur across the globe. Droughts would tend to decrease biological activity, but the subsequent precipitation would lead to "pulses" of CO_2 emissions to the atmosphere (Birch, 1958). Understanding the effects of temperature and soil moisture regime on SOC dynamics, especially in carbon-storing soils, and assessing the sensitivity of carbon mineralization to these climatic events is necessary to anticipate future carbon losses in terrestrial ecosystems under climate change. Climate change will obviously also play on C inputs to soil which will influence SOC stock evolution, but this is outside the scope of our present study.

Conant et al. (2011) define temperature sensitivity as the rate of a process (decomposition, desorption) at a given temperature compared to a control temperature. Temperature sensitivity, determined by Q_{10}, represents a proportional increase (or decrease) in SOC mineralization for a temperature increase of a 10 °C (Kirschbaum, 1995). The Q_{10} is an important parameter for predicting the fates of SOC under warmer climate (Kan et al., 2020). Findings of other studies showed that Q_{10} values varied largely across the range of temperatures (Ghosh et al., 2016, 2018). Contrary to temperature, there is no standardized parameter to assess the sensitivity of carbon mineralization to soil moisture regime. In this study, we defined moisture sensitivity as the proportional response of soil microbial respiration (SOC mineralization) of soils exposed to different moisture levels relative to a control moisture. In addition to climatic factors, the quality of soil organic matter should also affect the rate of decomposition (Guntiñas et al., 2013). In soils formed under similar climates and from similar parent material, the quality of the organic matter depends on the vegetation cover, the quality of external organic input and the type of use and management to which the soil is subjected. So, the implementation of agroecological practices including conservation agriculture, organic agriculture and organic waste products application (composts, manure) affects the quantity and quality of organic matter in soils which, in turn, can play on the sensitivity of SOC mineralization to climate change.

No-tillage and crop rotation types under conservation agriculture affect the distribution of carbon in soil fractions (Zhang et al., 2020b). Some research suggests that additional C from increased residue inputs accumulates mostly in particulate organic matter (POM) fractions that are on average easily mineralized and only small gains occur in the resistant C pool (Bhattacharyya et al., 2011, Mitchell et al., 2018). Long-term organic waste supply significantly increased the POM fractions (Peltre et al., 2012, Paetsch et al., 2016). These results show that the implementation of agroecological practices increasing C inputs may affect SOC temporal stability. However, there is a lack of consensus in the literature on how SOC accumulated under alternative practices respond to seasonal climate variability and projected climate change (Davidson and Janssens, 2006, Carey et al., 2016). The carbon loss through heterotrophic respiration is intrinsically related to the availability and quality of this organic carbon (Lindén et al., 2014, Hopkins et al., 2014). The POM fraction is believed to be a quite labile carbon pool in soils, with a mean residence time up to 20 years (Balesdent et al., 1998). Therefore, if additional SOC carbon mainly comprises POM, as suggested in the literature, then the sensitivity of SOC mineralization to temperature and moisture regime under agroecological practices (carbon-storing soils) could differ from that of soils where agroecological practices have not been implemented (baseline soils). Indeed, previous studies have shown that labile carbon is less sensitive to temperature than stable carbon (Liski et al., 1999, Conen et al., 2008, Lefèvre et al., 2014, Xu et al., 2014). Based on these findings, we hypothesized that SOC mineralization in carbon-storing soils would be relatively less sensitive to temperature. Conversely, soil moisture affects the oxygenation of these POMs and their accessibility to decomposers by increasing the probability of contact between organic substrates and microorganisms (Monard et al., 2012). Thus, the sensitivity of SOC mineralization to soil moisture regime is expected to be relatively higher in carbon-storing soils than in their baseline soils. Testing these hypotheses is crucial to provide knowledge that will allow to identify the best management practices that reduce CO_2 emissions and enhance the soil carbon sink effect, even under climate change.

We aimed to investigate in this study two related research questions. The first objective was to assess the sensitivity of SOC mineralization to the soil moisture regime in carbon-storing soils compared to baseline soils. To achieve this objective, we incubated in the laboratory soils collected from long-term field experiments at different matric potentials (pF 1.5; pF 2.5 and pF 4.2) and subsequent dry (pF 4.2)-wet (pF 1.5) cycles at 20°C and monitored continuously SOC mineralization in the incubation flasks. We calculated the delta SOC mineralized due to the change in soil moisture to assess the sensitivity of SOC mineralization to soil moisture regime. The second objective was to assess the sensitivity of SOC mineralization to temperature increase in carbon-storing soils. To do this, we also incubated replicates of the same soils in the laboratory at three temperatures (20, 28 and 35°C) in optimal moisture (pF 2.5). We calculated Q_{10} using the equal carbon respired method (Conant et al., 2008) to assess the sensitivity of SOC mineralization to temperature in carbon-storing soils and baseline soils.

2. Materials and methods

2.1. Field site and soil sampling

This study focuses on two French long-term experiments (LTEs) where agroecological practices including conservation agriculture, organic agriculture and the application of organic waste products with contrasting biochemical quality have resulted in increased soil organic carbon contents and stocks relative to the baseline practices, i.e., conventional agriculture (Table. 1). This increase was named "additional soil organic carbon" (e.g., Bamière et al., 2022), and we used the term "carbon-storing soils" to refer to these soils that had stored additional carbon under agroecological practices.

La Cage LTE is conducted in Versailles (48°48'N,2°08'E). During the studied period (1998-2020), the mean annual temperature and precipitation were 11.6 °C and 633 mm respectively (Fig. 1). The soil is a well-drained deep Luvisol (WRB, 2015). The experimental field is arranged in a randomized complete block design, divided into two blocks, themselves divided into four plots for each cropping system, and then into two subplots of 0.56 ha, so that wheat is present every year in one of the 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. It differed in conservation agriculture (CA) and organic agriculture (ORG) for some years, with the replacement of rapeseed by maize (*Zea mays L.*) in CA or the introduction of alfalfa (*Medicago sativa*) in CA and ORG.

- 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.
- CA includes a permanent soil cover, initially fescue (*Festuca rubra*) and since 2008 alfalfa, grown under the main crops, except pea. The soil is not tilled.
- ORG is characterized by an alfalfa-alfalfa-wheat-wheat rotation. No pesticides nor mineral fertilizers are used.

The QualiAgro LTE is located at Feucherolles, 20 km west of Versailles (48°52′N, 1°57′E) (Fig. 1). The soil is a Luvisol (WRB, 2015), cultivated for 21 years with a conventional wheat-maize rotation (Peltre et al., 2012). The mean annual temperature and precipitation for the last 20 years are 11 °C and 614 mm respectively. It is an LTE conducted in collaboration with INRAE and Veolia Environment

Research and Innovation since 1998, on which composts of organic waste products (OWPs) are applied every 2 years before tillage, at a dose equivalent to ~4 t C. ha^{-1} from 1998 to 2013 and ~2 t C. ha^{-1} from 2015 to 2020. The completely randomized block comprised an area of 6 ha with 40 plots of 450 m^2 each and 4 replicates per treatment. Since 2015, wheat and maize residues are buried in the soil. Three organic amendments are considered in this study and compared to a conventional agriculture treatment without organic inputs (CON-QA):

- 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 the reference amendment in the region.

Soils from both LTEs were sampled at 30 ± 1 cm depth and stored in a chamber at 4°C after sieving to <4 mm a composite sample per plot.

2.2. Laboratory incubations

Surface soils (0-30cm) sieved to <4 mm was used for a microcosms incubation experiment to determine the effects of temperature (T°C), soil moisture (pF), and dry-wet-cycles (DWC) on SOC mineralization. Before incubating the soil samples, a water content and matric potential response curve was established using Richard's presses. The water contents at saturation and corresponding to pF 1.5, pF 2.5 and pF 4.2 were determined for soils under each agricultural practice considered in this study (results presented in Table S1).

2.2.1. Soil cylinder construction and pre-incubation

Polyvinyl chloride (PVC) cylinders 5.7 cm in diameter and 4 cm in height with 2 mm perforations were used. A 50 µm mesh cloth at the bottom of the cylinder provided support for the soil while promoting gas exchange. Each cylinder was weighed empty and then with fresh soil equivalent to 100g dry 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 adding water with a pasteur pipette. Then the microcosms were mounted in 1L jars. The soil cylinders were placed on PVC supports and 15 mL of water was added to the bottom of the jars to stabilize the moisture. The jars were closed and the whole set was put in the incubator at 20°C for a one-week pre-incubation. Four replicates per agricultural practice and per moisture regime or temperature were prepared.

2.2.2. Experiment with soil moisture regime

To evaluate the effect of soil moisture regime on SOC mineralization, 4 soil moisture scenarios were performed and applied at 20°C: a continuously wet scenario at pF 1.5 (WET); a continuously moderated wet scenario at pF 2.5 (MWET); a continuously dry scenario at pF 4.2 (DRY) and a five subsequent dry-wet cycles scenario (DWC). To obtain the continuously moisture scenario after pre-incubation at pF 2.5, we added deionized water using a pasteur pipette to bring the replicates dedicated for WET scenario to pF 1.5. For replicates dedicated to MWET scenario (pF 2.5), we checked if the soil moisture corresponded to pF2.5. For the replicates dedicated to the DRY scenario, we introduced 50 g of silica-gel during the pre-incubation phase to dry the soil. As soon as the moisture level corresponding to pF4.2 was reached, we removed the silica-gel from the jars. For DWC scenario, five dry–wet cycles were implemented during the experimental period (97 d). Each cycle contained two phases, 10 days of drying phase, followed by 7 days of moist phase after rewetting. The drying phase consisted of adding silica gel to the incubation jars to absorb the soil water and allow for a gradual soil drying. For this, perforated PVC cylinders containing 50 g of silica gel were added to each jar and changed after 6 days when the jars were vented after measuring the CO_2 concentration in the headspace by micro-chromatography. A preliminary experiment had allowed to establish the amount of silica gel needed to dry the soil samples to pF 4.2 in 10 days. At the end of the drying period, rapid rewetting was performed by adding deionized water (the amount of water needed to reach pF 1.5) with a pasteur pipette. The same procedure was repeated for 5 times to simulate the dry-wet cycles in the soils. The four scenarios are schematized in Fig. 2.

2.2.3. Experiment with increased temperatures

To evaluate the effect of temperature on carbon mineralization, 3 temperature scenarios were compared: 20°C; 28°C and 35°C, using four replicates per scenario. The soil cylinders were kept at constant moisture (pF2.5). After the one-week pre-incubation the jars were placed either in an incubator set at 20°C, or in a thermostat chamber at 28°C and at 35°C and incubated for 92 days. We maintained constant soil moisture by weighing each sample after each CO_2 measurement and adjusting the moisture content to the target mass.

2.2.4. Mineralization monitoring

Soil organic carbon (SOC) mineralization was monitored regularly for 97 days, with measurements on days 1, 3, 7, 13, 17, 24, 28, 34, 41, 45, 51, 59, 63, 69, 76, 80, 86 and 97 for each soil moisture scenario, and on days 1, 3, 7, 15, 22, 30, 37, 52, 65, 79 and 92 for each temperature scenario. SOC mineralization was measured non-destructively using a gas micro-chromatograph (µGC 490; Agilent Technologie; USA). The absolute amount of CO_2 emitted is measured in parts per million (ppm). It is then converted to µg C-CO_2 g^{-1} dry soil with the following formula:

$$\mu g\ C\text{-}CO_2.g^{-1}\ \text{dry soil} = \frac{CO_2\ (ppm) * M_c * V_b}{V_M * M_{soil}}$$

(1), (Védère et al., 2020), with CO_2 (ppm): amount of CO_2 emitted measured by gas micro-chromatograph; Mc: molar mass of carbon in g.mol^{-1}; V_b: volume of the jar in L; V_M: molar volume of gas in L.mol^{-1} and M_{soil}: mass of incubated soil in g. Then 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.

2.2.5. Soil moisture effect and sensitivity of SOC mineralization

The soil moisture effect on SOC mineralization was determined by calculating the delta SOC mineralized i.e., the difference in specific SOC mineralized between the high moisture (WET), low-moisture (DRY) and dry-wet-cycle (DWC) with specific SOC mineralized under optimal moisture (MWET). A negative value indicates an inhibition of SOC mineralization, while a positive value indicates a stimulation of SOC mineralization. Furthermore, to assess the sensitivity of carbon-storing soils to the soil moisture regime, we compared the delta SOC mineralized under WET, DRY, and DWC between baseline soils (CON-LC and CON-QA for La Cage and QualiAgro LTEs, respectively) and soils under agroecological practices, i.e., CA, ORG, MSW, FYM and BIOW.

2.2.6. Temperature sensitivity of SOC mineralization

The Q_{10} was used in this study to estimate the sensitivity of organic carbon mineralization under different agricultural practices to temperature increase. The method for calculating Q_{10} at equal carbon mineralized (Q_{10}-q) described by Conant et al. (2008) was carried out in this study. This method involves determining the amount of time needed for a given amount of SOC to be respired at a given temperature. The time required to respire a given amount of SOC at two temperatures is then used to calculate a Q_{10} value. This method of analysis eliminates the problem of fixed incubation duration leading to comparison of different SOC pools, which confounds characterization of temperature sensitivity (Reichstein et al., 2000, 2005, Leifeld & Fuhrer, 2005). Therefore, the Q_{10} was calculated for 1% and 3% of respired SOC. The Q_{10} is calculated for 2 temperature ranges (20-28°C and 28-35°C) with the following formula:

$$Q_{10}\text{-q} = \left(\frac{t1}{t2}\right) e\left(\frac{10}{(T2-T1)}\right)$$

(2) (Conant et al., 2008), with t_1 and t_2 the time required to respired the same amount of carbon at low temperature (T_1) and high temperature (T_2).

2.3. Statistical analysis

All data were tested for normality and homogeneity of variance. Log-transformation was applied, if the transformation improved the normality and variance substantially. A one-way ANOVA with Tukey's test was used to detect the differences in Q_{10}, the delta SOC mineralized and the amount of SOC mineralized among soil moisture and temperature scenarios within each field site, then across all scenarios in both sites. When the normality or homogeneity of the data was not confirmed, we applied the non-parametric Kruskal-Wallis test. All statistical analyses were completed in R (version 4.0.2).

3. Results

3.1. Soil carbon mineralization under diverse moisture regimes, temperatures and agricultural practices

Increasing soil moisture significantly affected SOC mineralization in the La Cage and QualiAgro LTEs (Table. 2; $p<0.05$). Also, SOC mineralization followed a polynomial function with the soil matric potential (Fig. 3). Carbon mineralization under soil moisture regime was in this order: WET=MWET>DWC>DRY. To better observe the effect of soil moisture regime on carbon mineralization, we considered the MWET as the moisture control in order to calculate the delta SOC mineralization induced by the change in soil moisture. The delta SOC mineralized in the WET scenario compared to MWET was on average +0.07 to +1.10 % of SOC (Fig. 6), showing a lack of or a weak stimulation of SOC mineralization with increasing soil moisture above pF 2.5 (Fig. 6). The delta SOC mineralized was significantly larger at La Cage (CON-LC: 1.10 ± 0.45; ORG: 0.89 ± 0.76 and CA: 0.69 ± 0.52% of SOC) than at QualiAgro (CON-QA: 0.12 ± 0.43; MSW: 0.24 ± 0.24; FYM: 0.07 ± 0.12 and BIOW: 0.30 ± 0.10% of SOC) ($p<0.05$; Fig. 6). Increasing the soil moisture from pF2.5 to pF1.5 did not significantly increase carbon mineralization at QualiAgro. In contrast, the DWC and DRY scenarios inhibited carbon mineralization relative to MWET scenario (Fig. 6). SOC mineralization in DWC decreased on average between 1.15 to 2.16 % of SOC and in DRY scenario on average between 2.35 to 2.97 % SOC (Fig. 6). This result suggests that multiple dry-wet cycles (DWC) did not stimulate carbon mineralization relative to the optimum soil moisture (MWET), whereas multiple DWC stimulated carbon mineralization relative to the low moisture scenario (DRY).

Increasing temperature also significantly affected cumulative SOC mineralization in both LTEs (Table 3; $p<0.05$). Except the CON-LC where no significant difference was found between mineralization at 20 and 28°C, the soils under other agricultural practices showed significant differences between 20, 28 and 35°C (Table. 3; $p<0.05$).

At QualiAgro, we observed a significantly larger specific SOC mineralization in the reference plots (CON-QA) compared to the plots that received organic waste products (CON-QA>BIOW=FYM

=MSW), whatever the soil moisture regime and temperature (Fig. 5, Fig. 7c, Fig. 7d), indicating less stabilization of SOC in CON-QA. However, at La Cage, regardless of soil moisture regime and temperature (Fig. 4, Fig. 7a, Fig. 7b), there was no difference in specific mineralization rates between the treatments (ORG, CA) relative to the conventional agriculture (CON-LC).

In addition, the effect of agricultural practices in both LTEs reported in Table 2, indicates that CON-LC baseline practice at La Cage and the CON-QA baseline practice at QualiAgro, not only had similar SOC contents (9.82 ± 0.48 g $C.kg^{-1}$ and 10.11 ± 1.12 g $C.kg^{-1}$ respectively) but also had the same percentage of mineralized SOC whatever the soil moisture regime. Moreover, the percentage of SOC mineralized under agroecological practices at La Cage (CA: 2.24 to 5.61 % SOC and ORG: 2.56 to 6.38 % SOC) was significantly larger than under organic waste products application (MSW: 1.46 to 4.09 % SOC; FYM: 1.48 to 4.06 % SOC and BIOW: 1.23 to 3.89 % SOC) (Table. 2). Also, when comparing the agroecological practices in both LTEs, we found that the agroecological practices at La Cage (ORG and CA) generated more SOC loss than agroecological practices at QualiAgro (BIOW, MSW, and FYM) after 3 months of incubation at diverse temperatures (Table. 3).

3.2. Sensitivity of SOC mineralization to soil moisture regime

The analysis of variance (ANOVA) revealed that within each LTE, we observed no significant difference between the carbon-storing soils (CA, ORG, MSW, FYM and BIOW) and their respective baseline soils (CON-LC and CON-QA) in the delta SOC mineralized whatever the soil moisture regime (Fig. 6). These results indicate that the carbon-storing soils had a similar sensitivity to the soil moisture regime as the baseline ones.

3.3. Sensitivity of SOC mineralization to temperature increase

The mean Q_{10} corresponding to equal 1% mineralized SOC at QualiAgro ranged between 1.90 to 2.53 for the 20-28°C temperature range, compared to 1.38 to 1.55 at La Cage (Fig. 8). These Q_{10} did not change significantly from 1% to 3% mineralized SOC (Table S2). Furthermore, the Q_{10} for the temperature range 20-28°C was larger for the BIOW plot than for the CON-LC plot (Fig. 8; $p<0.05$), but no significant difference was found between agroecological practices (CA, ORG, MSW, FYM and FYM). For the temperature range 28-35°C we did not observe any significant difference between agricultural practices (Fig. 8, $p>0.05$). The SOC under OWPs practices (BIOW, FYM and MSW) had the same sensitivity of SOC mineralization to temperature as their baseline practice (CON-QA), as did the CA and ORG with their baseline practice (CON-LC). These results indicate that carbon-storing soils had a similar sensitivity of SOC mineralization to temperature increase as the baseline soils.

4. Discussion

4.1. Soil carbon mineralization under soil moisture regime and temperature

The interaction of soil microbes with their physical environment affects their ability to mineralize SOC into CO_2. One of these environmental factors is soil moisture (Cook & Orchard, 2008). The results of the present study indicated that SOC mineralization followed a polynomial function with soil matric potential (Fig. 3). Manzoni et al. (2012) and Moyano et al. (2012) in their meta-analyses found for their dataset that the soil heterotrophic respiration (mineralization) decreased steadily when the matric potential became more negative, i.e., for high pF values. This result agrees with ours, where SOC mineralization decreased as we reach higher pFs (pF1.5 ≥ pF2.5>pF4.2), i.e., lower matric potentials (-0.015 MPa ≥ -0.033 MPa > -1.6 MPa). Such a decrease in respiration is associated with a reduction in solute diffusivity in mineral soils at low soil moisture (pF4.2), because water-filled capillaries become disconnected as the soil becomes drier (Moldrup et al., 2001). Therefore, solute diffusivity (and thus substrate and nutrient bioavailability) may be the most limiting factor under dry conditions (Skopp et al., 1990, Schjønning et al., 2003, Or et al., 2007, Moyano et al., 2013). Conversely, increasing soil moisture increases solute diffusion rates in soils, enhancing the accessibility of substrates by soil microorganisms (Monard et al., 2012, Moyano et al., 2013, Manzoni and Katul, 2014). Our results are consistent with the hypothesis that higher soil moisture increase the accessibility of SOC to decomposers and thus lead to more SOC mineralization than low moisture contents, provided the soil moisture remains well below saturation, where oxygen diffusion rates becomes a limiting factor for heterotrophic respiration (Cook and Orchard, 2008, Moyano et al., 2013).

In addition, the percentage of SOC mineralized at pF1.5 (WET) after 97 days are statistically identical to the percentage at pF2.5 (MWET) (Table. 2), implying that the increase in soil moisture beyond pF2.5 did not result in significant further CO_2 emission to the atmosphere. This result suggests that at pF2.5, the mineralization optimum was reached, and increasing soil moisture to pF1.5 does not yet alter SOC mineralization due to slight anoxia. Because the diffusion rate of oxygen through water is much lower than through air (Cook and Knight, 2003), the metabolic activity of aerobic organisms also decreases as soil pore space fills with water and approaches saturation levels (Franzluebbers, 1999). Curtin et al. (2012) showed that the optimum matric potential for mineralization can be as high as -0.005 MPa; while the meta-analysis by Moyano et al. (2012) found an optimum matric potential for mineralization of -0.001 MPa corresponding to pF 1. In our case, we observed no decrease in SOC mineralization in the wettest state, i.e., -0.015 MPa (pF1.5). One possible explanation is that the soil was sieved and repacked and the cores had a high inter-aggregate macroporosity favorable to air circulation, preventing anoxia, or that at pF1.5 a slight anoxia at compensated for a better substrate diffusion compared to pF2.5 resulting in similar SOC mineralization rates at pF1.5 and 2.5.

The dry-wet cycles scenario tested in this study did not induce substantial delta SOC mineralization when compared to optimum moisture (MWET), but did if compared to low moisture (DRY) scenario (Table. 2). The drying phase induced low carbon mineralization rates as a result of reduced microbial activity (Franzluebbers et al., 1994, Pulleman and Tietema, 1999) and decreased accessibility of the organic substrate to decomposers (Manzoni et al., 2012). This low mineralization was not compensated by the flush observed after rewetting (Mikha et al., 2005, Yemadje et al., 2017). Zhang et al. (2020) in their meta-analysis showed that, on average, dry-wet-cycles stimulated soil carbon mineralization by 72% relative to mineralization at low-moisture and inhibited carbon mineralization by 25% relative to incubation at high-moisture which is consistent with our results. Relevant controls are indeed needed when evaluating the importance of the Birch effect (Kpemoua et al., 2023).

Temperature generally had a positive effect on cumulative SOC mineralization, which was manifested by larger CO_2 emissions at higher temperatures (Table. 3). Similar increases in SOC mineralization with increasing temperature have previously been observed in many other studies (e.g., Conant et al., 2008, Ghosh et al., 2016, Ghimire et al., 2019, Fu et al., 2020). Temperature rise affects most of the physiological activity of microbial cell and accelerates residue decomposition (Reichstein et al., 2000, Yun et al., 2019).

4.2. Soil carbon mineralization under agricultural practices

We observed no significant difference in specific SOC mineralization rate between conventional agriculture (CON-LC) and agroecological practices (ORG and CA) at La Cage, whatever soil moisture regime and whatever the temperature. This result supports previous results obtained by Autret et al. (2020) on the same LTE, where soil incubation at pF 3 reported similar specific carbon mineralization between alternative practices (conservation, organic and low input agriculture) and conventional agriculture. Some studies (Dendooven et al., 2012, Ussiri and Lal, 2009) did measure lower SOC mineralization rates under no tillage, ascribed to less favorable local climatic conditions and better physical protection of organic matter in the soil structure (Balesdent et al., 2000). Similarly to our results, Zhang et al. (2020b), showed that tillage had no influence on specific C mineralization, while the interaction of tillage and depth had a significant effect. In the present study, we incubated samples from the surface to a depth equivalent to the soil mass of 4300 kg. ha^{-1} (corresponding to 30 ± 1 cm), regardless of agricultural practice. No-tillage typically results in carbon stratification in the soil (e.g., Zhao et al., 2015). We hypothesize that the physical protection of carbon is increased in the first 10 cm under no-tillage, but that considering a 0-30 cm soil layer cancels out this effect. Another hypothesis is that sieving the soils to <4 mm before incubation would have removed the physical protection occurring in macroaggregates in the CA soils.

At the QualiAgro LTE, the application of organic waste products (MSW, FYM and BIOW) reduced significantly SOC mineralization, compared to conventional agriculture without organic inputs (CON-QA) whatever soil moisture regime and whatever the temperature. These results can be explained by the fact that composts and farmyard manure have previously undergone a period of decomposition and therefore mineralize less rapidly than crop residues that contain higher proportions of easily mineralizable organic carbon (Chodak et al., 2001, Leifeld et al., 2002). The physico-chemical composition of the organic waste products (OWPs) has been analyzed by Peltre et al. (2012) at the QualiAgro LTE. They show that residual municipal solid waste compost (MSW) is the OWP with the least lignin, and biowaste compost (BIOW) the one with the most. Lignin is known to be a compound resistant to microbial degradation at a year to decadal timescale, which would explain why BIOW tends to mineralize less SOC than MSW and FYM (Table. 2). In the same way, an incubation study of substrates of different quality showed that manure is less biodegradable than crop residues such as straw and suggests that this is due to a more stable chemical quality, as manure is already biodegraded during animal digestion and storage (Benbi and Khosa, 2014). Fortuna et al. (2003) found that easily mineralizable C constituted less of the SOC in soils fertilized with compost as compared with soils that were fertilized with mineral N. Other studies have also shown that the application of organic amendments that include composts and manure have the potential to reduce CO_2 emission per unit of SOC since these best management practices contribute to carbon stabilization (Dou et al., 2008, Bhowmik et al., 2017).

Overall, the cumulative specific SOC mineralization in our incubations was much less for soils that received organic waste products plus crop residues (MSW, FYM, BIOW) than for soils receiving only crop residues (CON-QA, CON, ORG, CA) (Table. 2 and Table. 3). This result thus confirms that soils that received organic waste were depleted in labile SOC compared to soils that received only crop residues. In contrast to our results, Obriot (2016) had observed similar proportions of soil organic carbon mineralization between the conventional system without organic inputs and plots that had received 7 successive applications of organic waste products. We assume that the long-term application (11 successive applications in our study) of organic waste products led to a greater stabilization of carbon in the soil, which makes it less biodegraded by microorganisms.

4.3. Sensitivity of SOC mineralization to soil moisture regime

The results of the delta SOC mineralized due to soil moisture regime change indicated no significant difference between carbon-storing soils (CA and ORG) and the baseline soil (CON-LC) at La Cage (Fig. 6). These results suggest that the decomposability of organic carbon is similar under the contrasted agricultural practices whatever the soil moisture regime, or the environmental conditions for decomposers are the same (Autret et al., 2020). Regarding the decomposability of the organic carbon, it is likely that the nature of organic inputs to soil is rather similar as soil organic matter exhibits similar C/N ratio (Table. 1) and wheat is cropped one year out of two in all plots (Autret et al., 2016). The sensitivity of SOC mineralization to soil moisture regime is not affected by the cropping system nor tillage practice in this LTE.

At the QualiAgro LTE, the delta SOC mineralized due to changes in soil moisture regime also showed no significant difference between the baseline soil (CON-QA) and carbon-storing soils (MSW, BIOW and FYM). This result indicates that although the SOC in the baseline soil is more biodegradable on average, it has similar sensitivity of carbon mineralization to soil moisture regime than the SOC of carbon storing soils. The results in both experiments are contrary to our initial hypothesis concerning the higher sensitivity of carbon mineralization to soil moisture regime in carbon-storing soils relative to their baseline. Therefore, in a drier, wetter, or dry-wet conditions, the agroecological practices implemented in both LTEs are still beneficial for climate change mitigation.

4.4. Sensitivity of SOC mineralization to temperature increase

We found that the Q_{10} values (20-28°C: 1.38, 1.52 and 1.55 respectively for CON-LC, CA and ORG) were not significantly different under the contrasted agricultural practices at La Cage (Fig. 8). These results are contrary to those reported by Parihar et al. (2019), who found the extent of increase in mineralization with temperature elevation to be higher under conventional agriculture (high Q_{10}) than under conservation agriculture (low Q_{10}) whatever the soil depth. They justified their results by the high physical protection of the SOC under conservation agriculture limiting its accessibility to soil microbial degradation (Six et al., 2002). However, Autret et al (2016, 2020) had found in the La Cage LTE that the increase in carbon stocks in conservation agriculture was mainly due to the carbon input rather than to the expected physical protection. This result confirms ours, leading us to assume that neither tillage practice nor cropping systems affected the sensitivity of SOC mineralization to temperature increase. So, the carbon-storing soils (CA, ORG) at La Cage had a similar sensitivity of SOC mineralization to temperature increases as the baseline soil (CON-LC).

At QualiAgro, the Q_{10} value (Fig. 8) also did not reveal any significant difference between the agricultural practices (20-28°C: 1.90; 2.44; 2.37 and 2.52 for CON-QA, MSW, FYM and BIOW respectively). These results suggest that the carbon-storing soils (MSW, FYM, BIOW) at QualiAgro and the baseline soil (CON-QA) had the same sensitivity of SOC mineralization to temperature increase. This result contrasts with Benbi and Khosa (2014) who showed that temperature sensitivity depends on the quality of the substrate, and that manure is more sensitive (Q_{10} = 3) than green waste which is easily decomposable (Q_{10} = 2.5). However, they measured the mineralization of manure and green waste directly and not the soils that were amended with manure or green waste as we did.

In summary, the Q_{10} values obtained in the present study were generally close to the values reported in the meta-analysis by Hamdi et al. (2013) for agricultural soils. No differences were observed between the agricultural practice in both LTEs on their temperature sensitivity, although slightly higher Q_{10} values were observed at QualiAgro, especially in OWPs practices than in conservation and organic agriculture. To test the robustness of this result, we also calculated the Q_{10} calculated for 3% of SOC being mineralized in the incubations. We found it was not significantly different, neither across agricultural practices nor from the Q_{10} calculated for 1% SOC mineralized (Table S2). This result suggests that the carbon pool mineralized during 3 months incubation had similar quality and sensitivity whatever the agricultural practice.

5. Conclusion

While a diversity of agroecological management options allow to store additional organic carbon in soil, a remaining question concerns the permanence and vulnerability of this stored carbon. This study examined the response of soil organic carbon stored by agroecological practices to climate change. We found that the heterotrophic respiration of “carbon-storing soils” had similar sensitivities compared to their baseline counterparts, regarding soil moisture regime changes and temperature increases. Hence, the implementation of these agroecological practices appears beneficial for climate change mitigation, even in the context of extreme climatic events.

Here were assessed the sensitivity of soils managed under different agricultural practices to climate change, i.e., according to IPCC (2001) the degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. IPCC considers that the vulnerability to climate change is wider, as it encompasses also the capacity to adapt to climate change. In further studies, other aspects could be accounted for, such as the soils capacity to retain water, which our results suggest to be increased in the carbon-storing soils, the changes moisture and temperature regime consequent to the presence of a mulch, such as in conservation agriculture, or to changes in albedo, consequent to OWPs applications.

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Table 2 Soil organic carbon content according to agricultural practices, percentage of SOC mineralized according to soil moisture scenario: continuously wet scenario at pF1.5 (WET); continuously moderated wet scenario at pF2.5 (MWET); continuously dry scenario at pF4.2 (DRY) and Dry-wet cycles scenario (DWC). SOC: soil organic carbon; CON-LC: conventional agriculture; ORG: organic agriculture; CA: conservation agriculture; CON-QA: conventional agriculture without organic waste products; MSW: residual municipal solid waste compost; FYM: farmyard manure; BIOW: biowaste compost. NS: non-significant; ANOVA: analysis of the variance. (ϒ): p-value of soil moisture regime effect on SOC mineralization and (⊥): p-value of agricultural practices effect. Uppercase letters represent differences between soil moisture scenarios and lowercase letters represent differences between agricultural practices. A significant difference is obtained for $p<0.05$.

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Fig. 8. Q_{10} values distribution according to agricultural practices. On the left the Q_{10} for the temperature range 20-28°C and on the right the Q_{10} for the range 28-35°C. The red dots inside the boxplot represent the mean value whose numerical value is indicated above. A significant difference between agricultural practices is obtained for $p<0.05$.

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LTEs	Agricultural practices	Tillage modality	Block	Clay	Silt	Sand	C	N	C/N	pH_{H20}	Exchangeable cations ($Cmol^{+}.kg^{-1}$)				CEC
				$g.kg^{-1}$							K^{+}	Na^{+}	Ca^{2+}	Mg^{2+}	$Cmol^{+}.kg^{-1}$
La Cage 1998			-				9.85	0.99	9.95	7.37	-	-	-	-	11.52
La Cage 2020	CON-LC	Tillage	1	170	560	270	10.05	0.88	11.55	7.20	0.546	0.039	13.80	1.78	11.10
			2				9.25	0.91	10.15	7.15	0.584	0.039	13.30	1.75	9.85
	ORG		1				10.60	0.99	10.65	6.90	0.395	0.039	13.40	1.97	10.10
			2				10.05	0.95	10.60	7.20	0.474	0.039	13.00	2.01	9.80
	CA	No Tillage	1				13.55	1.32	10.25	7.15	0.707	0.039	13.95	2.28	10.95
			2				12.05	1.06	11.50	7.15	0.679	0.039	13.70	2.33	10.75
QualiAgro 1998			-				10.39	1.12	9.25	6.80	0.442	0.021	8.298	0.494	9.71
QualiAgro 2020	CON-QA	Tillage	-	156	778	65	10.11	1.04	9.65	6.74	0.270	0.032	7.67	0.455	8.25
	MSW		-				13.38	1.31	10.25	7.77	0.375	0.053	10.19	0.533	10.75
	FYM		-				14.30	1.41	10.16	7.31	0.922	0.039	8.65	0.950	10.27
	BIOW		-				16.62	1.66	9.12	7.71	0.610	0.04	10.86	0.650	11.77

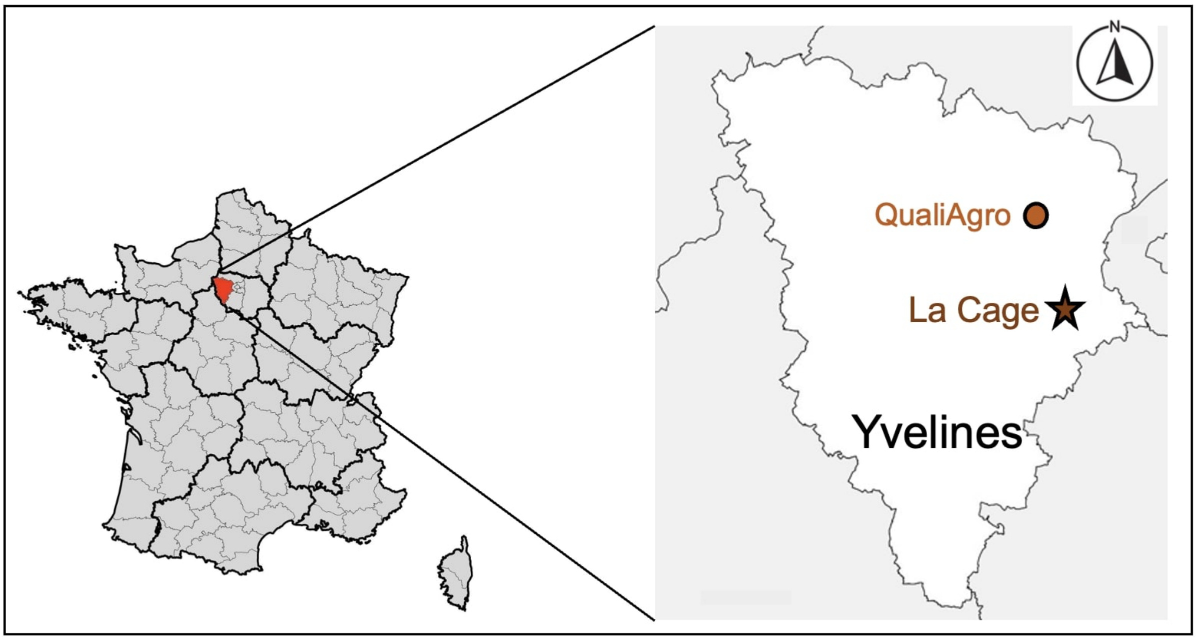
Table. 2 Soil organic carbon content according to agricultural practices, percentage of SOC mineralized according to soil moisture scenario: continuously wet scenario at pF1.5 (WET); continuously moderated wet scenario at pF2.5 (MWET); continuously dry scenario at pF4.2 (DRY) and Dry-wet cycles scenario (DWC). SOC: soil organic carbon; CON-LC: conventional agriculture; ORG: organic agriculture; CA: conservation agriculture; CON-QA: conventional agriculture without organic waste products; MSW: residual municipal solid waste compost; FYM: farmyard manure; BIOW: biowaste compost. NS: non-significant; ANOVA: analysis of the variance. (ϒ): p-value of soil moisture regime effect on SOC mineralization and (⊥): p-value of agricultural practices effect. Uppercase letters represent differences between soil moisture scenarios and lowercase letters represent differences between agricultural practices. A significant difference is obtained for $p<0.05$.

LTE	Agricultural practices	SOC g.kg^{-1}	% SOC mineralized WET	MWET	DWC	DRY	p-value $^{(\Upsilon)}$ ANOVA
La Cage	CON-LC	9.82 ± 0.48^{d}	5.53 ± 0.44^{abA}	4.43 ± 0.74^{aA}	3.27 ± 0.47^{abC}	1.93 ± 0.26^{abD}	*p<0.05*
	ORG	10.39 ± 0.42^{d}	6.38 ± 0.52^{aA}	5.57 ± 0.31^{aA}	3.33 ± 0.43^{aC}	2.56 ± 0.33^{aD}	
	CA	13.30 ± 1.05^{b}	5.61 ± 0.88^{abA}	4.67 ± 0.26^{aA}	3.28 ± 0.67^{abB}	2.24 ± 0.26^{aC}	
QualiAgro	CON-QA	10.11 ± 1.12^{d}	4.79 ± 0.26^{bcA}	4.92 ± 0.22^{abA}	3.22 ± 0.26^{abB}	1.95 ± 0.49^{bcC}	*p<0.05*
	MSW	13.38 ± 0.45^{b}	4.09 ± 0.48^{cA}	3.86 ± 0.33^{bA}	2.55 ± 0.08^{bB}	1.46 ± 0.19^{cC}	
	FYM	14.31 ± 0.63^{ab}	4.06 ± 0.24^{cA}	3.99 ± 0.24^{bA}	2.65 ± 0.11^{bB}	1.48 ± 0.17^{cC}	
	BIOW	15.81 ± 1.23^{a}	3.89 ± 0.25^{cA}	3.58 ± 0.18^{bA}	2.43 ± 0.19^{bB}	1.23 ± 0.08^{cC}	
p-value $^{(\perp)}$ ANOVA		*p<0.05*	*p<0.05*	*p<0.05*	*p<0.05*	*p<0.05*	

Table. 3 Percentage of SOC mineralized according to temperature increasing. (ϒ): p-value of incubation temperature effect on SOC mineralization and (⊥): p-value of agricultural practices effect. Uppercase letters represent differences between temperature scenarios and lowercase letters represent differences between agricultural practices. A significant difference is obtained for p<0.05.

LTEs	Agricultural practices	% SOC mineralized 20°C	28°C	35°C	p-value $^{(\Upsilon)}$ ANOVA
La Cage	CON-LC	4.28 ± 0.72^{aA}	5.90 ± 1.07^{bA}	7.96 ± 0.79^{bB}	*p<0.05*
	ORG	5.37 ± 0.31^{aA}	7.37 ± 0.52^{abB}	8.35 ± 0.36^{bC}	
	CA	5.01 ± 0.24^{aA}	7.26 ± 0.33^{abB}	8.55 ± 0.52^{bC}	
QualiAgro	CON-QA	4.77 ± 0.48^{aA}	7.89 ± 0.91^{aB}	9.54 ± 0.46^{aC}	*p<0.05*
	MSW	3.74 ± 0.33^{bA}	6.01 ± 0.67^{bB}	7.91 ± 0.29^{bC}	
	FYM	3.87 ± 0.23^{bA}	6.13 ± 0.42^{bB}	8.40 ± 0.44^{bC}	
	BIOW	3.47 ± 0.18^{bA}	5.87 ± 0.51^{bB}	7.52 ± 0.41^{bC}	
p-value $^{(\perp)}$ ANOVA/Kruskal test		*p=0.02*	*p<0.05*	*p<0.05*	

Fig. 1: Map of the Yvelines department (France) showing the location of the two field sites.



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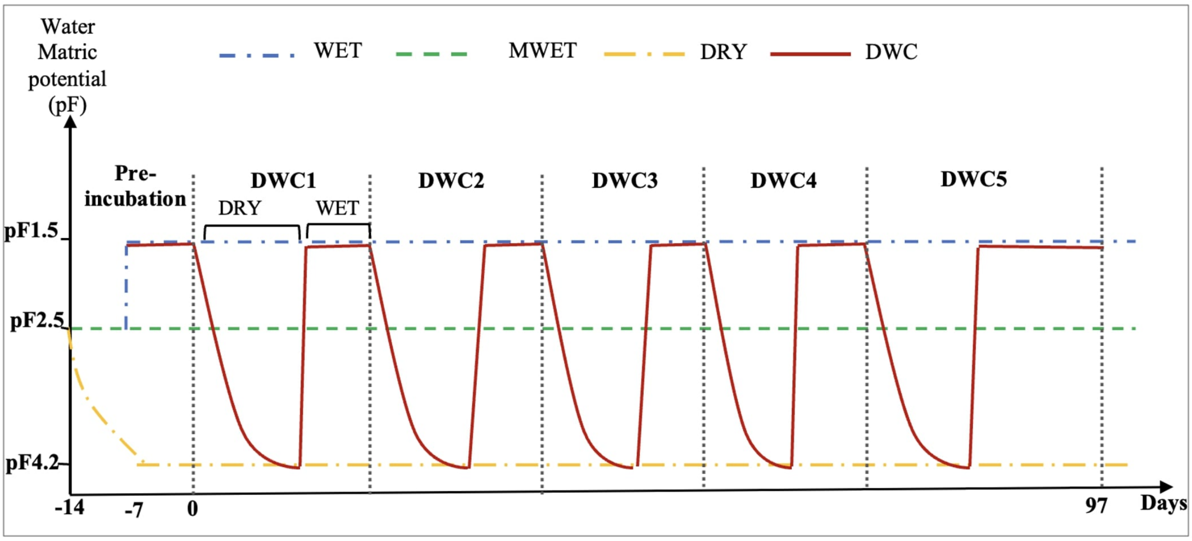

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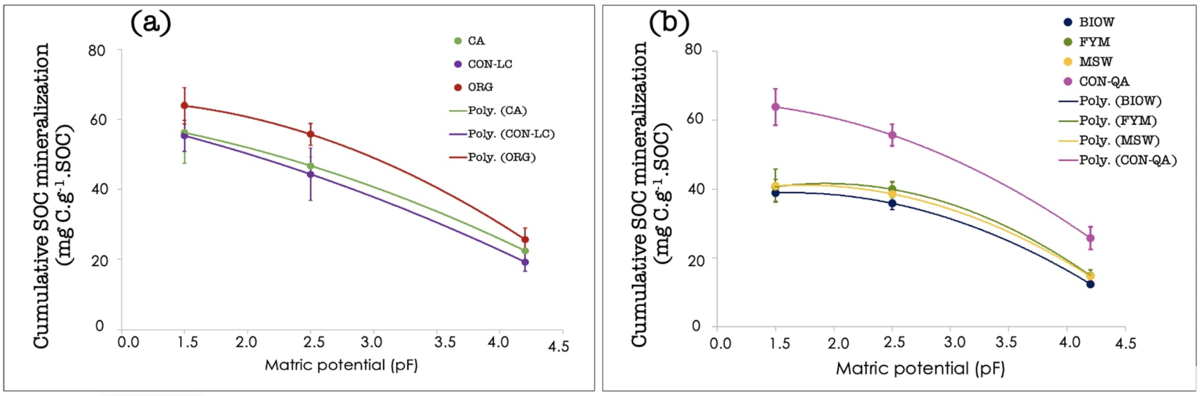

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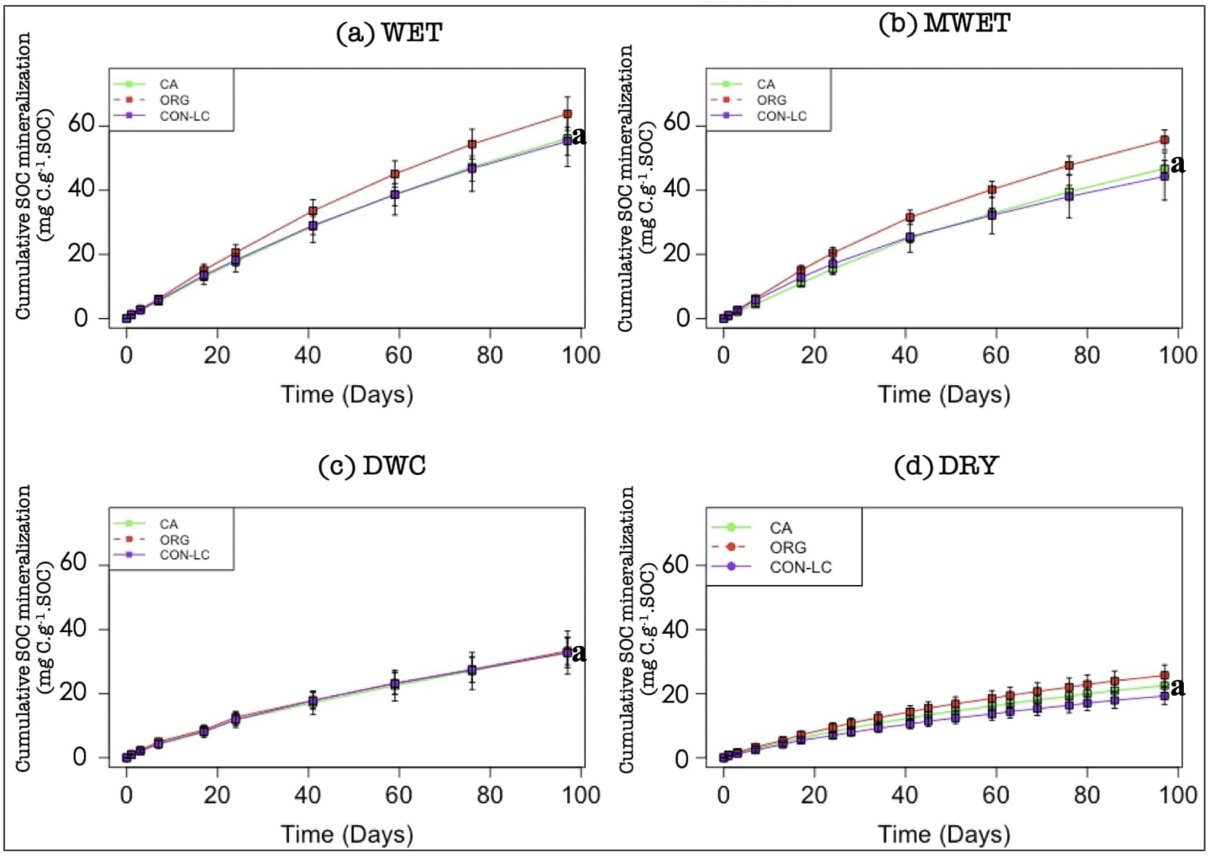

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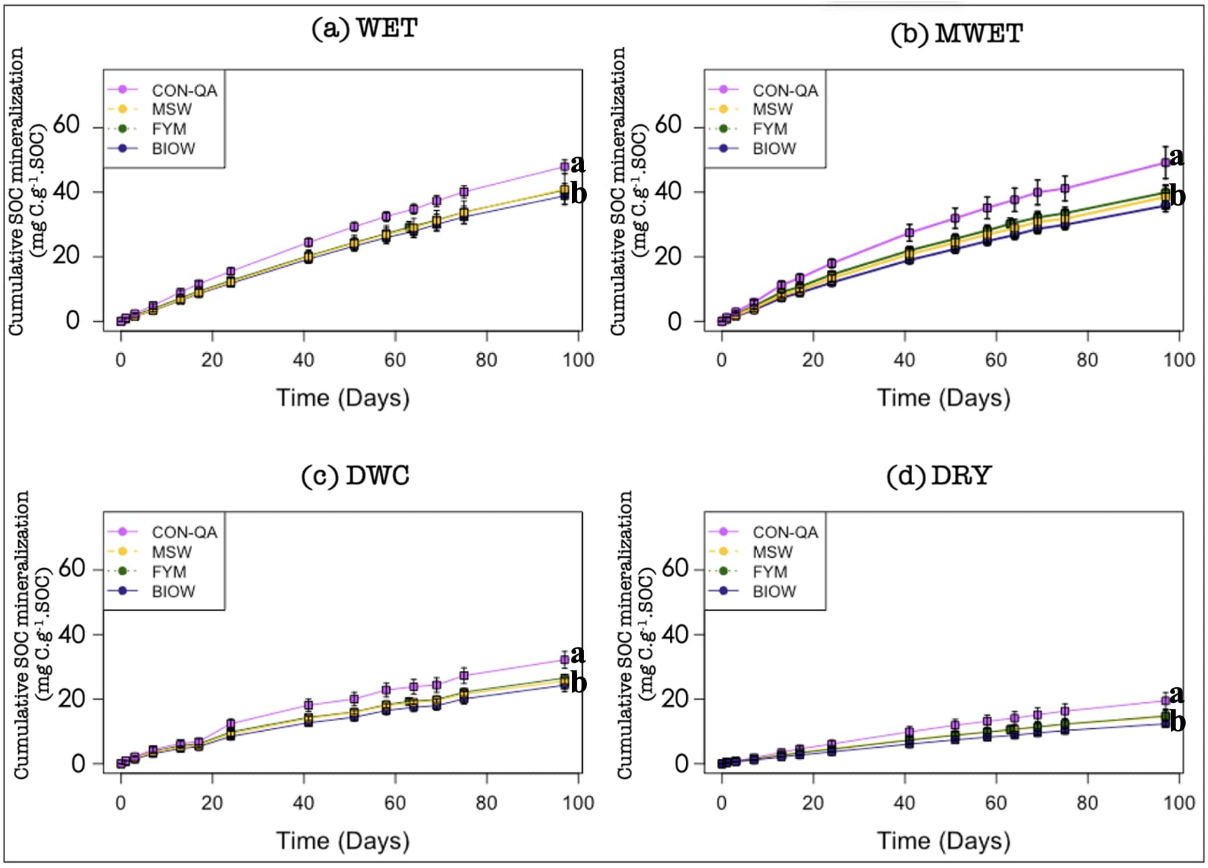

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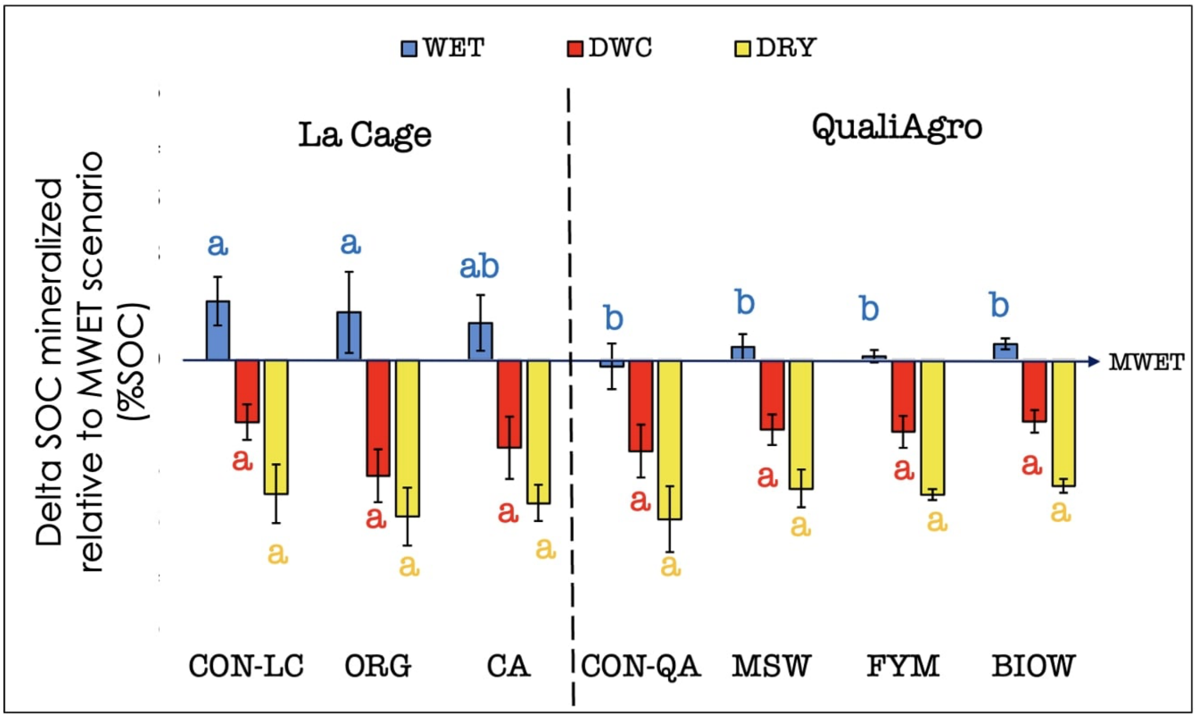

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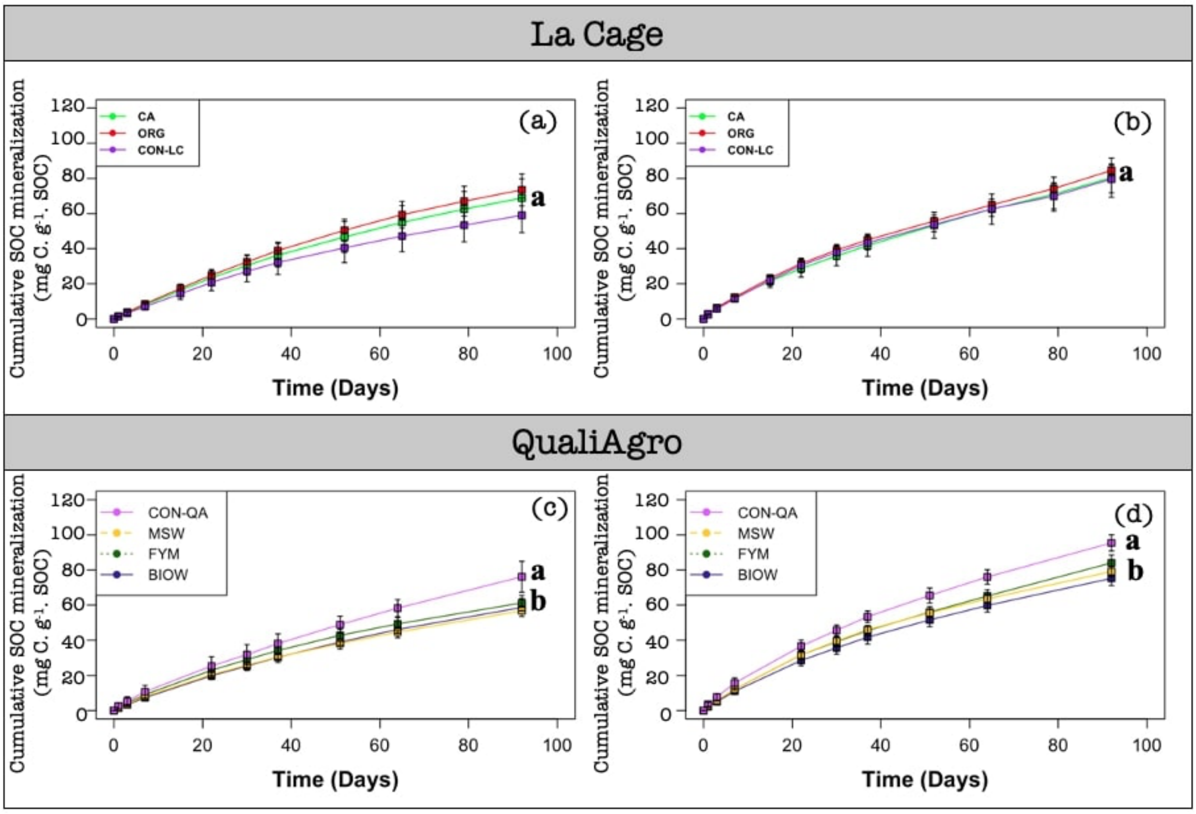

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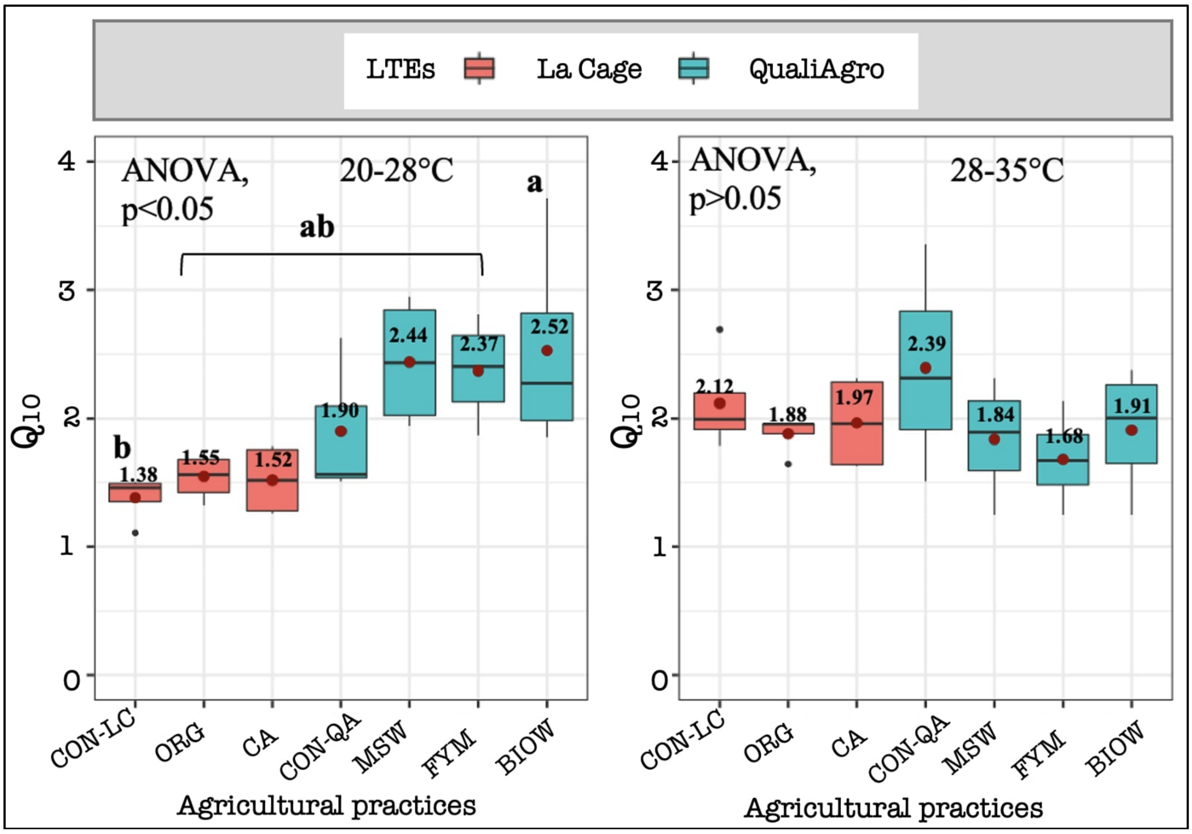

Supplementary materials for:

Are carbon-storing soils more sensitive to climate change? A laboratory evaluation for agricultural temperate soils

Tchodjowiè P. I. Kpemoua[1,3], Sarah Leclerc[1], Pierre Barré[2], Sabine Houot[1], Valérie Pouteau[1], Cédric Plessis[1], Claire Chenu[1]

[1] UMR Ecosys, Université Paris-Saclay, INRAE, AgroParisTech, Palaiseau, 91120, France

[2] Laboratoire de Géologie, UMR 8538, Ecole Normale Supérieure, PSL Research University, CNRS, Paris 75005, France

[3] Agence de la Transition Écologique, ADEME, 49004 Angers, France

Corresponding author:

E-mail address: claire.chenu@inrae.fr (C. Chenu)

Table S1: Measured mass water contents for matric potentials pF 1.5; pF 2.5 and pF 4.2

LTEs	Agricultural practices	pF1.5 -0.015 MPa	pF2.5 -0.033 MPa	pF4.2 -1.6 MPa
		W ($gH_20.g^{-1}$ soil)		
	CON-LC	0.29 ± 0.01	0.26 ± 0.00	0.09 ± 0.02
La Cage	ORG	0.30 ± 0.01	0.27 ± 0.03	0.13 ± 0.02
	CA	0.30 ± 0.01	0.27 ± 0.02	0.12 ± 0.02
	CON-QA	0.25 ± 0.02	0.22 ± 0.01	0.09 ± 0.01
QualiAgro	MSW	0.26 ± 0.01	0.22 ± 0.00	0.10 ± 0.01
	FYM	0.26 ± 0.01	0.23 ± 0.01	0.10 ± 0.01
	BIOW	0.26 ± 0.03	0.23 ± 0.00	0.10 ± 0.01

Table S2: Q_{10} values equal to 1% and 3% SOC mineralized according to cropping systems for the temperature range between 20-28°C and 28-35°C.

LTEs	**Agricultural practices**	Q10 equal to 1% of SOC mineralized		Q10 equal to 3% of SOC mineralized	
		20 - 28°C	28 – 35°C	20 - 28°C	28 – 35°C
	CON-LC	1.38 ± 0.18	2.12 ± 0.40	1.66 ± 0.19	2.08 ± 0.75
	ORG	1.55 ± 0.19	1.88 ± 0.16	1.57 ± 0.17	1.49 ± 0.20
La Cage	CA	1.52 ± 0.29	1.97 ± 0.38	1.62 ± 0.28	1.42 ± 0.28
	CON-QA	1.90 ± 0.63	2.39 ± 0.93	1.80 ± 0.46	2.32 ± 0.68
	MSW	2.44 ± 0.51	1.84 ± 0.47	2.57 ± 0.86	2.02 ± 0.66
	FYM	2.37 ± 0.42	1.68 ± 0.37	2.36 ± 0.39	1.83 ± 0.58
QualiAgro	BIOW	2.53 ± 0.84	1.91 ± 0.51	2.45 ± 0.37	1.90 ± 0.39