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Soil carbon storage and mineralization rates are affected by carbon inputs rather than physical disturbance: evidence from a 47-year tillage experiment

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Abstract

In spite of the large number of studies conducted on the drivers of soil organic carbon (SOC) stocks, there is still no consensus on the impact of tillage on the distribution and turnover rate of SOC in the soil profile. Few studies have characterized precisely the turnover of SOC using ^{13}C natural tracing or simulated the SOC evolution per soil layer. In this study, we combined several approaches (diachronic analysis of SOC stocks, isotopic tracing and modelling) for characterizing the SOC evolution per soil layer in one of the oldest tillage experiments comparing no-till (NT), shallow till (ST) and full inversion tillage (FIT) combined with six crop managements. The new measurements made in 2017 reported in this paper confirm that i) tillage had no effect on SOC stocks integrated over the old ploughed layer (~0-28 cm) or deeper (~0-58 cm) and ii) reduced tillage affected the SOC distribution in the soil profile, with SOC storage in the upper layer (~0-10 cm) offset by a SOC loss in the underlying layer (~10-28 cm). The change in rotation (from C4 to C3 crops) in two crop management treatments allowed to quantify the decrease in C4 stocks during 19 years and calculate the specific mineralization rates relative to tillage treatments and soil layers. The mineralization rates did not vary significantly between tillage treatments in the whole (old) ploughed layer (~0-28 cm) but varied according to depth and tillage. The highest rates were found in the layer 0-5 cm of NT or ST and the lowest rates in the layer 10-28 cm of the same tillage treatments. The rates were highly correlated with estimated C inputs and particulate organic matter contents in each layer, but not with tillage intensity. The evolution of total SOC and C4 stocks of each soil layer was simulated with AMG model during 47 years. The standard model (with a single mineralization rate) gave a good prediction of SOC evolution when applied to the whole profile (~0-28 cm) but not for each individual layer. Including a relationship between C input and mineralization rate in the model allowed to well simulate the SOC evolution in all soil layers. This study shows that the main effect of a change in tillage on SOC storage is the change in the distribution of C input throughout the profile and the corresponding variation of the priming effect rather than the change in physical soil disturbance.

1. **Introduction**

The reduction and even suppression of tillage in arable soils has been proposed as one tool for enhancing carbon storage in soils leading to C sequestration (*e.g.* UNEP report, 2013). However, there is no consensus yet on the real impact of this technique. Powlson *et al.* (2014) indicated that "*the quantity of additional organic carbon in soil under no-till is relatively small and in large part an apparent increase resulting from an altered depth distribution*". They pointed out that weaknesses in sampling methodologies, assumptions and interpretations in C sequestration studies comparing no-till (NT) to conventional tillage (CT) are causing overstatements of the potential of sequestering C in no-till soils.

Soil tillage may affect either the amount of C input in soil or the C output flux, *i.e*. the C mineralization rate. Both effects can occur. The total input of C may vary in relation with crop yield and crop biomass returned to soil including belowground (BG) materials. Crop yields have been shown to be comparable or slightly lower under NT than under CT (*e.g*. Pittelkow *et al*., 2016). In their meta-analysis, Virto *et al.* (2012) have shown that the variation in C input was a major factor explaining the variability in soil organic C storage due to tillage. But the main effect of tillage consists in altering the distribution of C inputs derived from aboveground (ABG) crop residues within the soil profile: no till systems receiving all ABG residues at soil surface whereas residues are mixed within tilled layers in tilled systems. The only sources of C input below soil surface in no-till systems are the root deposition and the transport of organic matter from the surface by bioturbation. Many studies have focused on the C stock in the upper soil layer (0-5 or 0-10 cm) under reduced tillage and few of them have analyzed the impact of the variation in C distribution within the profile.

The second possible effect of tillage is a modification in the C output flux. Six *et al.* (1999) suggested that NT management could result in a decrease of the decomposition rate of organic matter derived from original vegetation as one possible mechanism for increasing C sequestration. Several studies involving ^{13}C natural tracing suggested that the mean residence time (MRT, inverse of mineralization rate) could be higher under NT, probably due to an increase in physical protection of organic matter (Balesdent *et al*., 2000). However other studies (Murage *et al*., 2007; Haile-Mariam *et al*., 2008) found no difference in MRT between NT and CT systems. Therefore, no clear conclusion can be drawn up to now.

Methodological reasons can explain the discrepancies in results concerning C sequestration and turnover. A rigorous assessment of SOC stocks and SOC changes throughout time requires to follow five methodological recommendations: i) direct measurement of bulk density; ii) deep sampling, so that the sampling depth exceeds the maximum tilled depth (Luo *et al*., 2010; Olson and Al-Kaisi, 2015); iii) calculation of stocks on an equivalent soil mass (ESM) and not on a depth basis (Wendt and Hauser, 2013); iv) pretreatment baseline measurement in the plots before treatments are applied (Olson, 2013) and v) use of a diachronic (*i.e.* a time series analysis) rather than a synchronic approach (Costa Junior *et al*., 2013; Olson *et al*., 2014). The latter authors indicated that "*to unequivocally demonstrate that the SOC sequestration has occurred at a specific site, a temporal increase must be documented relative to pretreatment SOC content*". However, the diachronic analyses are rare (Dimassi *et al*., 2014a).

Another source of divergence between published results concerns the evolution of SOC content below the upper soil layer (below 10 cm) under reduced or no-till (NT) compared to conventional tillage with ploughing (called HT or CT). The last meta-analysis made by Meurer *et al*. (2018) suggests that the mean difference NT-HT remains positive when the depth increases while the meta-analyses of Angers and Eriksen-Hamel (2008) and Luo *et al*. (2010) showed that the difference NT-CT becomes negative in soil layers between 15 and 40 cm. This divergence emphasizes the interest of a rigorous analysis of the SOC stocks in various layers and not simply in a single layer. It also suggests the interest of modelling the evolution of SOC stocks in various soil layers in order to test whether the main drivers of SOC evolution both at soil surface and below are well understood.

In this paper, we examine the effect of contrasted soil tillage and crop management on SOC evolution in a long-term experiment (LTE) which is one of the oldest tillage experiment worldwide including a full diachronic analysis. We had three objectives: i) evaluate the consistency of the diachronic approach described by Dimassi *et al.* (2014a) for quantifying SOC storage after 47 years under contrasted tillage treatments; ii) characterize and disentangle the effects of C inputs and tillage operations on C mineralization rates in each soil layer; iii) evaluate the ability of the original or modified AMG model (Clivot *et al.*, 2019) to predict the evolution of SOC stocks in each soil layer. The originality of our approach consists in i) applying the methodological recommendations cited above, ii) following the SOC distribution throughout the soil profile and its evolution throughout time, ii) assessing our understanding of the SOC evolution through modelling.

2. Materials and Methods

2.1. Experimental design

The ongoing LTE on soil tillage, referred to as Experiment A, was established in 1970 at the experimental station of Arvalis at Boigneville in Northern France (48°19'37'' N, 2°22'56'' E). Details of the experiment can be found in Dimassi *et al.* (2014a) and Labreuche *et al.* (2018), including soil characteristics. The field is flat with a good internal drainage, so that no erosion takes place between plots or outside. The soil is a Haplic Luvisol developed on loess and contains 24% clay, 65% silt and 9% sand. The average annual temperature, precipitation and potential evapotranspiration were 10.9°C, 627 and 736 mm over the whole study (1970-2017) and 11.7°C, 637 and 746 mm respectively during the last measurement period (2011-2017).

Three tillage treatments were established in 1970: no-till (NT), shallow tillage (ST) and full inversion tillage (FIT). In 1970, at the onset of the experiment, the soil was ploughed at a depth of *ca.* 28 cm. The ploughing depth was reduced progressively after 1970 to 25 cm down to 22 cm in the last years. Mouldboard ploughing was realized in FIT every year at the end of autumn; superficial tillage (5-10 cm deep) was performed in ST every year either with rotavator or shallow mouldboard plough in order to favour crop residues decomposition. Seedbed preparation at sowing was similar in FIT and ST, and often consisted in two operations: rotary harrow and tine harrow (0-5 cm depth). No tillage was practiced continuously in the NT treatment.

The layout consists in a randomized block system with four blocks. In addition to tillage treatments, six crop managements were established successively during four periods (Fig. 1). During the first period (1970-1982), all plots were cropped with a maize/winter wheat rotation and crop residues were chopped and spread at soil surface after harvest: this defines the first crop management (CM1) which was continued until 2017. During the second period (1982-1998), crop residues were removed from half of the plots creating a new crop management (CM6). Crop residues of CM6 were removed during the first 12 years (1982-1994) and returned again to soil in the following years. In 1998, half of the blocks were converted to a new 4-year rotation (winter wheat / barley / sugarbeet / pea) yielding two new crop managements without C4 crops (CM3 and CM4), CM3 deriving from CM1 and CM4 deriving from CM6. During the fourth period (2002-2017), plots corresponding to CM1 and CM6 were split into two subplots, half of them being managed as previously and the other half receiving a catch crop (oats/vetch) after wheat crop, yielding two crop managements: CM2 derived from CM1 and CM5 derived from CM6. All crops of the rotation were present every year in each crop management. Fertilization was similar in all tillage treatments. The mean N application rate was 175 kg ha^{-1} yr^{-1}.

2.2. Soil sampling

Soil sampling strategy was designed to calculate SOC stocks on ESM basis over a depth greater than the deepest tillage event ever made. Soil samples were collected in 1970, 1974, 1978, 1982, 1986, 1990, 1994, 1998, 2002, 2007, 2011 and 2017. All details concerning the sampling methodology practiced until 2011 are given in Dimassi *et al.* (2014a). In 2017, sampling was realized with a hydraulic gauge (Apageo, Magny, France) to pull out intact soil cores of 6 cm diameter and 70 cm height. Each core was divided into seven subcores (layers 0-5, 5-10, 10-15, 15-28, 28-33, 33-40 and 40-60 cm). Two soil cores were collected in each plot and gathered together, giving 504 samples (3 tillage x 6 crop management treatments x 7 layers x 4 replicates). Each sample was dried at 35°C and weighed in order to calculate its exact depth according to the measured bulk density.

Bulk densities were determined simultaneously in all plots over the whole profile, using a cylinder method for the upper 0-5 cm layer, a gamma densitometer (LPC-INRA, Angers, France) in the layers 5-40 cm (every 5 cm), and by weighing soil cores in the 40-60 cm layer. A total of 576 measurements was realized.

2.3. Soil and plant analysis

Coarse residues and roots present in the fresh soil cores were removed by handpicking. Soil samples were oven dried at 35°C for 96 hours, crushed to pass through a 2 mm sieve and finely ground with a ball mill (PM 400, Retsch, Germany). All soil samples since 1970 were analyzed for total carbon and nitrogen concentrations and ^{13}C abundance using an elemental analyzer (EURO EA, Eurovector, Milan, Italy) coupled to an isotope ratio mass spectrometer (Delta Plus Advantage, Thermo Electron, Germany). The presence of $CaCO_3$ was checked in all plots and layers. A few soil samples (essentially in the layer 40-60 cm) containing more than 1 g $CaCO_3$ kg^{-1} soil were decarbonated with a few drops of HCl 1M and re-analyzed for organic C.

Soil pH in water was measured for the different soil layers and treatments in 1982, 1994, 2002, 2007 and 2017. Coarse particulate organic matter (CPOM) was determined on soil samples sampled between 1998 and 2011, as described by Autret *et al.* (2016). A 2 mm sieved and air dried soil sample of 50 g was dispersed under deionized water on a 200 µm sieve. Coarser particles (200–2000 µm) were washed out in a bucket during three minutes. Floating particles were collected (CPOM), oven dried at 60°C and finely ground with a ball mill. Their C concentration and ^{13}C abundance were determined as indicated previously.

Grain yields were determined every year in each plot as indicated by Dimassi *et al.* (2014a). ABG biomass was sampled at harvest in 2010, 2011 and 2012. Grain and straw samples were analyzed to determine their carbon concentration and ^{13}C abundance using the same method than for soil samples.

2.4. Calculation of SOC and SOC-C4 stocks

Calculations of SOC stocks were made at equivalent soil mass (ESM), using measurements of bulk density and organic carbon concentration. Comparing tillage treatments on ESM instead of soil depth basis is essential since no till results in changes in bulk density, with often lower bulk density in the 0-5 cm layer and increased bulk density in deeper layers (Powlson *et al.*, 2014). Calculations were made for six soil layers: L1 (700 t soil ha^{-1} corresponding to ~ 0-5 cm); L2 (800 t ha^{-1}, ~ 5-10 cm); L3 (800 t ha^{-1}, ~ 10-15 cm); L4 (1760 t ha^{-1}, ~ 15-28 cm); L5 (540 t ha^{-1}, ~ 28-33 cm) and L6 (4000 t ha^{-1}, ~ 33-60 cm). The reference soil mass in each layer was calculated using bulk densities measured in 1970 at the onset of the experiment. The reference mass in layer L1-4 (4060 t soil ha^{-1}, corresponding to about 0-28 cm) includes and exceeds the deepest tillage event made during the experiment. Layer L6 was sampled only in 2011 and 2017. All calculations made at ESM were realized using the method described in Autret *et al.* (2016) with a dedicated R package “SEME”, available on request (Mary *et al.*, 2018). Briefly, the soil is first discretized into elementary layers of 1 mm thickness. For a given plot and a given sampling year, a soil mass and a carbon concentration is assigned to each elementary layer *k*, depending on the measured layer to which it belongs. Then, the depth of SOC stock calculation (z) is determined each time to get as close as possible to the reference soil mass. Finally, the cumulative SOC stock $QC(z)$ (in t C ha^{-1}) in the layer 0-z is calculated as follows:

$$QC(z) = 0.01\sum_{k=1}^{z} \rho(k)\cdot C(k) \qquad (1)$$

where $\rho(k)$ and $C(k)$ are respectively the bulk density (g cm^{-3}) and the SOC concentration (g kg^{-1}) of the elementary layer *k*.

At the start of the experiment, SOC mainly derived from C3 crops (wheat, barley, etc.) with a small proportion of C4 crops (maize). The maize-wheat rotation practiced in all treatments lead to an increase in the SOC-C4 stock coming from the C4 crop (called thereafter SOC4). This stock was calculated classically (*e.g.* Balesdent *et al.*, 1990) as follows:

$$SOC4 = f \cdot SOC \tag{2}$$

with $$f = \frac{\delta - \delta_3}{\delta_4 - \delta_3} \tag{3}$$

where *f* is the proportion of SOC derived from C4 plants, δ is the δ^{13}C signature of the SOC, δ_3 and δ_4 are the δ^{13}C signatures of the C inputs derived from C3 plants and C4 plants respectively. The values of δ_3 and δ_4 are taken as the average of all analyses of ABG plant organs (δ_3 = -27.5 ‰ and δ_4 = -12.5 ‰). Similar calculations were made with the CPOM stocks.

2.5. Calculation of C mineralization rates

In the treatments CM3 and CM4, the mixed C3-C4 rotation (maize-wheat) established from 1970 to 1998 was converted into a 4-year C3 rotation between 1998 and 2017. This resulted in an increase in SOC4 followed by a drop after 1998. The SOC4 decay could be fitted to an exponential function:

$$SOC4 = \left(C_{04} - Cs_4\right) \cdot \exp(-k \cdot t) + Cs_4 \tag{4}$$

where C_{04} is the initial SOC4 stock (in 1998), *k* is the mineralization rate (expressed per unit of SOC, in yr^{-1}) of the *SOC4* stock and C_{s4} is an asymptotic value corresponding to the amount of stable carbon contained in the C4 stock. This function corresponds to equation (9) in Bernoux *et al.* (1998) who compared a single and double compartment model, and indicated that “when the derived systems are few decades old, it could be assumed that the more stable fractions are invariant over the period”. The amount of stable carbon was calculated by assuming that the percentage of stable carbon of C4 origin (Cs_4/C_{04}) in 1970 was similar in all layers and all treatments, since the soil of all plots had been mixed by annual ploughing until this date. This percentage was fixed at 35%, value which provided the best quality of fit. A sensitivity analysis of mineralization rates to this value was conducted.

2.6. Statistical analysis

All statistical analyses were performed using *R* (R Core Team, 2019). ANOVA was performed on C concentration, bulk density and SOC stock in each soil layer to evaluate the tillage and crop management effects in 2017. A linear mixed effect model was used with soil tillage and crop management as fixed factors and block as random factor. We used the *nlme* package (Pinheiro *et al*., 2018) to fit the model. Significant differences ($p < 0.05$) between tillage treatments were found using the *emmeans* function (Lenth, 2019). The assumptions of the linear mixed effect model were checked by visual examination of the residuals against predicted values and residuals histograms. Prior to SOC analysis, we used log transformed data or a Box-Cox transformation if necessary to meet assumptions of normality. The analysis was also applied to SOC stocks for layers L1-2, L3-5 and L1-5 at each sampling year from 1970 to 2017. The mineralization rates obtained from the SOC4 stocks kinetics in 1998-2017 for CM3 and CM4 treatments were analyzed using a second model, with tillage, crop management and layer as fixed factors and block as random factor.

2.7. C inputs calculation

Total C inputs (in layer L1-4) were calculated from crop yields as described by Clivot *et al.* (2019) using a methodology adapted from Bolinder *et al.* (2007). We used the measured data of dry matter yields and harvest indices to estimate ABG C inputs. We assumed that BG C inputs (root + extra-root C) were independent on crop yield but crop species dependent (see discussion in Clivot *et al*., 2019). The annual BG C input per species was calculated using the average yield of the given crop species over all treatments and years and relative plant C allocation coefficients. These coefficients together with the humification rates of crop residues were obtained from Clivot *et al.* (2019).

The distribution of C inputs derived from ABG residues between layers L1 to L4 was calculated over the maximum depth of tillage by considering that all ABG residues were distributed between the tilled layers proportionally to the soil mass of each layer, assuming that ABG residues were homogenously mixed within tilled layers. The tillage depth considered was: 25 cm in 1970-1979, 24 cm in 1980-1989, 23 cm in 1990-1997 and 22 cm in 1998-2017 for FIT; 10 cm in 1970-1998 and 5 cm in 1999-2017 for ST. ABG residues in treatment NT were supposed to enter layer L1 only. The distribution of C inputs derived from BG residues (roots + rhizodeposits) was first calculated using the asymptotic equation of Gale and Grigal (1987) and data retrieved from Fan *et al.* (2016) (see Clivot *et al.*, 2019 for more details). BG inputs distribution was then re-estimated for the tilled layers, assuming a distribution proportional to the soil mass, as for ABG inputs. The asymptotic root distribution was compared to the observed distributions reported by Qin *et al.* (2004, 2006): a very slight difference in root distribution was found between FIT and reduced tillage treatments (ST and NT). The C inputs calculated with the two methods were very close together and the asymptotic distribution was therefore used in the study.

2.8. Simulation of SOC stocks with AMG model

The evolution of SOC and SOC4 stocks were simulated using AMG model. This model simulates soil C dynamics at an annual time step and considers three organic matter pools: fresh organic C coming from crop residues or organic amendments and SOC which is divided into active and stable pools (Saffih-Hdadi and Mary, 2008). The last version of this model was successfully evaluated for predicting SOC evolution in a set of 20 long-term French experiments (Clivot *et al.*, 2019). The originality of our work consisted in simulating SOC evolution not only in the whole (old) ploughed layer (L1-4, corresponding to about 0-28 cm) but also in each individual layer (L1 to L4).

The mineralization rate of AMG model (k) is the product of the potential mineralization rate (k_0) and functions depending on soil characteristics (clay and $CaCO_3$ contents, C/N ratio and pH) and climate (temperature and soil moisture conditions). The results of the present study indicated that it can also vary with the amount of C input (called I). Regarding soil data inputs for AMG, clay and $CaCO_3$ contents were considered invariant and homogeneous between layers and treatments (239 and 0 g kg^{-1} respectively). Soil pH and C:N ratio were defined for each treatment, layer and year, according to the measurements and using linear interpolation between measurement dates. We used the default values of the model for the SOC partitioning in 1970: the initial proportion of the stable pool was set at 65% of total SOC and at 35% of total SOC4. The vertical distribution of C inputs within the soil profile was assumed to be mainly driven by tillage operations, the effects of bioturbation or liquid phase transport of organic matter being considered negligible compared to tillage. AMG model was run in three steps:

In a first step, the model was used in its standard version. We used the standard parameters of the soil mineralization model implemented in AMGv2 (Clivot *et al.*, 2019) including the standard potential mineralization rate (k_0 = 0.29 yr^{-1}). In a second step, the mineralization rates kij determined in treatments CM3 and CM4 using the SOC4 evolution during the period 1998-2017 were forced in all treatments and over time. In a third step, the model was modified to account for the relationship, called $k_0(I)$, found between mineralization rate and C inputs. The modified version (AMGv3) calculates a potential mineralization rate specific of each layer, tillage and crop management treatment depending on its C input. Two relationships were tested: i) a linear function:

$$k_0(I) = \alpha + \beta \cdot I \qquad (5)$$

and an exponential function:

$$k_0(I) = \alpha + (k_{00} - \alpha)(1 - \exp(-\beta \cdot I)) \qquad (6)$$

where α represents the mineralization rate in the absence of C input, β is a shape parameter and k_{00} represents the asymptotic value of the mineralization rate.

3. Results

3.1. SOC stocks observed in 2017

The organic C concentrations measured in 2017 and the corresponding SOC stocks are given in Table S1. They exhibit very similar trends with the previous observations made until 2011 (Dimassi *et al.*, 2014a). SOC concentration varied little between crop management treatments and much more between tillage treatments, with no interaction between crop management and tillage. If we consider the mean of all crop management treatments (Table 1), SOC concentrations in ST and NT treatments were significantly higher than in FIT for layers L1 and L2 and significantly lower for layers L3 and L4. No difference could be detected between tillage treatments in layers L5 and L6.

Bulk density was also affected by crop management and tillage, justifying the calculation of SOC stocks at equivalent soil mass (Table S2). Compared to FIT, bulk density in reduced tillage treatments was smaller near soil surface (0-10 cm), higher in 10-20 cm and lower below the old ploughing depth (< 25 cm).

Calculated SOC stocks varied widely with depth and tillage. Reduced tillage resulted in higher SOC stocks in layer L1-2 (~ 0-10 cm) and lower stocks in layer L3-4 (~ 10-28 cm). A full compensation occurred between layers since no significant difference in SOC stocks was found between tillage treatments over the old ploughed layer (L1-4) and even down to 60 cm (L1-6), whatever the crop management treatment. The mean SOC stock in the whole profile (L1-6) of all crop managements was 65.2 ± 4.9, 66.0 ± 4.3 and 66.9 ± 3.7 t ha^{-1} for FIT, ST and NT, respectively.

3.2. Evolution of SOC stocks from 1970 to 2017

Fig. 2 shows the evolution of SOC from 1970 to 2017 in layers L1-2 (~ 0-10 cm), L3-5 (~ 10-33 cm) and L1-5 (~ 0-33 cm). It represents the mean of the six crop management treatments in view of the fact that no significant interaction was detected in SOC stocks between tillage and crop management (Dimassi *et al.*, 2014a). Layer L3-5 exceeds by about 5 cm the maximum depth ever tilled. In the FIT treatment, SOC stock in layers L1-2 and L3-5 increased very slightly with time. SOC content in layer L1-2 increased markedly and almost continuously in the reduced tillage treatments (ST and NT). Simultaneously SOC stock in layer L3-5 decreased almost continuously in these treatments. Compared to FIT treatment, the SOC content increased by 5.5 ± 0.8 and 5.5 ± 0.9 t C ha^{-1} in layer L1-2 and decreased by -4.9 ± 0.7 and -4.4 ± 0.8 t C ha^{-1} in layer L3-5 in treatments ST and NT respectively, during the period 1970-2017. When integrated over the two layers, *i.e.* below the maximum tillage depth (L1-5), the SOC stock followed exactly the same evolution in the three tillage treatments. The only significant difference which occurred in 1994 has been attributed to the climatic sequence (Dimassi *et al.*, 2014a).

3.3 Evolution of SOC-C4 stocks after a change in the crop rotation

In treatments CM3 and CM4, the change in rotation after 1998 from a mixed C3-C4 to a pure C3 crop rotation resulted in a marked change in the SOC4 dynamics (Fig. 3). The SOC4 stock in the old ploughed layer (0-28 cm) increased from 1970 to 1998 during the maize-wheat rotation and then decreased during the following pure C3 rotation. The evolution was very similar in the three tillage treatments: the only difference was the slightly smaller increase in the treatment NT during the period 1978-1988. It is attributed to a slightly smaller maize yield and therefore a smaller amount of maize residues returned to soil. After 1998, the decline of SOC4 in the whole (old) ploughed layer was exponential and similar in all tillage treatments.

Conversely, the evolution of SOC4 stock in each layer (*i*) for each tillage (*j*) differed widely among layers and tillage treatments (not shown). Each kinetics observed from 1998 to 2017 was fitted to the exponential model presented earlier (Eq. 4). The mineralization rates (called *kij*) thus obtained and the corresponding indicator of the quality of fit (relative RMSE) are given in Table 2. No significant difference was detected between treatments CM3 and CM4, so that they were considered together. The statistical analysis revealed that *kij* did not differ between layers under FIT, but differed in the reduced tillage treatments: it was about 50% higher in the surface layer (L1) than in the deeper layers (L2, L3 and L4). *kij* varied between tillage treatments, particularly in the upper layer: the mineralization rate in L1 was much higher in ST and NT (0.133 and 0.125 yr^{-1} respectively) than in the FIT treatment (0.081 yr^{-1}). This conclusion remains valid even if we change the parameter C_{s4}, *i.e.* the initial amount of stable carbon contained in the SOC4 stock. The sensitivity analysis showed that the differences between treatments were similar to those obtained with the standard value of C_{s4} (Table S4). It is noticeable that the mineralization rates, calculated for the whole (old) ploughed layer (L1-4, ~0-28 cm), were absolutely similar (0.080 ± 0.001 yr^{-1}) in the three tillage treatments. This result is also consistent with the evolution of the C4 content of particulate organic matter. The mineralization rate of the POM-C4 stock in layer L1-4 did not differ between tillage and crop management treatments (Fig. S1). Its mean value among tillage treatments was 0.42 ± 0.03 yr^{-1}.

3.4 Mineralization rates and C inputs per soil layer

The mineralization rates were then compared to the C inputs (Cij) calculated for each soil layer (i) and each tillage treatment (j). The C inputs were calculated annually and then averaged over two periods. Estimated total C inputs in the whole (old) ploughed layer (L1-4) increased from 3.04 ± 0.02 to 4.06 ± 0.06 t C ha^{-1} yr^{-1} between the first (1970-1998) and the second period (1998-2017), due to the increase in crop biomass production (Table 3 and S3). The total C inputs were very close between tillage treatments, as previously found for crop yields (Dimassi *et al.*, 2014a), but the distribution within the profile was very different. For example, C inputs in layer L3 were higher than those in layer L1 in the FIT treatment but represented only 5% to 7% of the C inputs in layer L1 of treatment NT.

When considering the 4 layers and the 3 tillage treatments, we found a close relationship (Fig. 4) between the C mineralization rates (kij) previously determined from the SOC4 stock dynamics and the C inputs (Cij, expressed in g C kg^{-1} soil) calculated during the same period (1998-2017). The regression line was $kij = 0.015\ Cij + 0.060$ ($r^2 = 0.93$; $p < 0.001$). In fact, the relationship was even better described by a non-linear function, as follows: $kij = 0.185\ (1 - \exp(-0.102\ Cij)) + 0.059$. The interest of the latter function is to simulate an asymptotic increase of the mineralization rate when C input increases (asymptotic value = 0.244 yr^{-1}), as expected. We also found a close correlation between *kij* and the mean CPOM content (*P*, expressed in g C kg^{-1} soil) measured over the period 1998-2011 (Fig. S2): $kij = 0.067\ P + 0.052$ ($r^2 = 0.93$; $p < 0.001$). Such a relationship is not surprising since CPOM is expected to be a proxy for the amount of C input.

3.5 Simulation of SOC stocks per soil layer with AMG model

AMG model was run for each layer, tillage and crop management treatment (4 x 3 x 6 = 72 situations) in order to simulate the evolution of SOC and SOC4 stocks. The simulations were run either with the standard potential mineralization rate (k_0, step 1) or the mineralization rates specific of each layer and tillage treatment determined previously (*kij*, step 2). The comparison between simulated and observed stocks during two periods (1970-1998 and 1998-2017) is presented at Fig. 5.

We first analyze the second period (1998-2017) which was used for calculating the decay of SOC4 stocks in treatments CM3 and CM4. During this period, the quality of fit in the FIT treatment was about the same between the two mineralization options: the standard (k_0) and the specific one (*kij*). This was expected because *kij* varied little among soil layers in this treatment. The SOC stocks were rather well simulated in all layers and SOC4 stocks were slightly underestimated in L4 for both options. Conversely, the model prediction of SOC and SOC4 stocks was markedly improved in treatments ST and NT when considering the specific mineralization rates ~~which varied widely between soil layers~~ (Table S5). For example, the mean RMSE for the SOC stock in layer L1 of NT treatment dropped from 4.70 t C ha^{-1} with the standard mineralization rate to 1.22 t C ha^{-1} with the specific mineralization rate. Therefore, the conclusions made in CM3 and CM4 were valid for the other treatments: the soil layers receiving higher C inputs had greater mineralization rates than those receiving low C inputs. Our results also demonstrate that mineralization rates were not related to tillage intensity, for the following reasons: i) *kij* were similar in layer 1 of treatments ST and NT although this layer was tilled in

ST but not NT; ii) *kij* in layer 1 was higher in ST than FIT although layer 1 was tilled in both treatments (and even more in the FIT treatment).

However, during the first period (1970-1998), the predictions with the specific mineralization rates were not better than those realized with the standard mineralization rate. In particular, SOC stocks in layer L1 of ST and NT treatments were underestimated with the *kij* model. In these treatments, the model error was larger for SOC stocks but smaller for SOC4 stocks.

If we consider both periods (1970-2017), the quality of fit was improved when using specific mineralization rates, particularly in the first layer of reduced tillage treatments (Table 4). For example, the mean RMSE in layer L1 of NT treatment was 4.15 t C ha^{-1} with the k_0 mineralization rate and only 1.93 t C ha^{-1} with the specific mineralization rate. The quality of prediction of SOC4 stocks was also improved with the specific mineralization rates: for instance, the RMSE in layer L1 of NT treatment decreased from 2.21 t C ha^{-1} with k_0 to 0.56 t C ha^{-1} with *kij*.

3.6 Evaluation of the new mineralization rate model

The new mineralization rate model including equations (5) or (6) was implemented in AMG model (AMGv3) and compared to the standard version (AMGv2). AMGv3 assumes that the potential mineralization rate k_0 increases when the C input increases, either linearly (Eq. 5) or exponentially (Eq. 6). The parameters α, β and k_{00} were fixed using the regression equation (Fig. 4). The quality of fit was similar using the linear or the exponential relationship. We therefore used only the exponential relationship for comparison with AMGv2. Increasing the C input from 1.0 to 4.0 g C kg^{-1} soil yr^{-1}, which corresponds approximately to the change which occurred after 1970 in layer L1 of treatments ST and NT (0.7 to 2.8 t C ha^{-1} yr^{-1}), should have almost doubled the potential mineralization rate, from 0.31 to 0.55 yr^{-1}. Conversely, the reduction in C input from 1.0 to 0.2 g C kg^{-1} soil yr^{-1}, which occurred in layer 4 of the same treatments, would have slightly decreased the potential mineralization rate, from 0.31 to 0.23 yr^{-1}.

The new mineralization model AMGv3 could reproduce very satisfactorily the evolution of SOC stocks in each soil layer in the three tillage treatments (Fig. 6.) If we consider the whole dataset, the quality of fit was good (Table 4), as indicated by the small MD and RMSE, most often smaller than the standard deviations of measurements (mean SD = 0.80 t C ha^{-1}). The quality of fit was better in the new model $k_0(l)$ compared to the *kij* model (fixed values of Table 2) and better than the standard k_0 model, since the average RMSE was 0.77, 0.93 and 1.26 t C ha^{-1} respectively, and the mean absolute MD was 0.34, 0.55 and 0.84 t C ha^{-1}. The new model greatly improved simulations in layer L1, which were poorly simulated by the standard k_0 model. These results confirm that the observed decline in the SOC stock in layers L3 and L4 of treatments ST and NT results mainly (if not exclusively) from the marked reduction in C inputs derived from ABG crop residues compared to FIT treatment or the initial situation.

If we consider the total SOC stock in L1-4 (~0-28 cm), summing up individual simulations of layers L1 to L4, AMGv3 performed better than AMGv2 for ST and NT treatments (Fig. 7, Table 4). Indeed, SOC stocks in these treatments were overestimated by AMGv2 after 1998. Furthermore, AMGv3 simulated a similar evolution of SOC stocks in the three tillage treatments, consistently with the observed data. Finally, when simulating directly the whole layer L1-4 (which is the default use of the model), both models gave similar results, close to the sum of individual simulations of layers L1 to L4 with AMGv3 (Fig.7).

4. Discussion

4.1. Tillage effects on SOC storage in the long-term

The diachronic analysis of SOC evolution in the soil profile of our LTE (47 years) confirms the results obtained in the same experiment (Dimassi *et al.*, 2014a) and in two other LTEs made on the same site (Dimassi *et al.*, 2013; Mary *et al.*, 2014): reduced tillage and even no-till did not result in permanent additional SOC storage compared to annual ploughing if SOC stocks are calculated over a depth equal or greater than the maximum tillage depth ever done. This conclusion is in line with the meta-analysis made by Luo *et al.* (2010) who selected experiments with a depth greater than 40 cm. It was obtained under a rather wet and temperate climate and may not apply to situations where crop yields differ widely between tillage systems or under semi-arid conditions (*e.g.* Blanco-Moure *et al.*, 2013). Many recent papers, such as Dikgwatlhe *et al.* (2014), Powlson *et al.* (2014), Olson and Al-Kaisi (2015), Singh *et al.* (2015), Valboa *et al.* (2015), Piccoli *et al.* (2016), Fujisaki *et al.* (2017), Martinez *et al.* (2017) or Hiel *et al.* (2018), confirm that the reduced tillage has a major impact on SOC distribution in soil but may not change the total SOC content when a sufficient depth is considered.

One originality of this paper is to make a diachronic analysis per layer, which is rarely done in the literature. We found a continuous increase of SOC stock in the upper layer of the reduced tillage treatments but also a continuous loss of carbon in the deeper layers (10-33 cm) which have not reached yet their SOC equilibrium. In comparison with FIT, the mean rate of change in layer L3-4 (10-28 cm) of treatments ST and NT was -0.10 ± 0.03 and -0.09 ± 0.04 t C ha^{-1} yr^{-1} (mean and confidence interval of the slope of the linear regression) respectively, corresponding to a loss of 18% and 16% of initial soil carbon after 47 years. Comparable SOC losses can be calculated in two diachronic studies reported in Spain: Hernanz *et al.* (2009) found that SOC stock in 10-40 cm had decreased by 14% and 19% after 20 years in ST and NT treatments respectively; López-Fando and Pardo (2011) observed a SOC loss of 23% and 31% respectively in the layer 10-30 cm after 16 years. The data of Clapp *et al.* (2000) from the Rosemount LTE (USA) shows a 7 to 30% decrease of SOC in 15-30 cm after 13 years. These high net decay rates (7-31%) challenge the commonly reported assumption that no-tillage reduces the C mineralization rate in the undisturbed soil layers, due to physical protection.

4.2. Mineralization rate estimates with ^{13}C tracing methodology

The change in crop rotation (from mixed C4/C3 to exclusive C3 plants) realized in treatments CM3 and CM4 from 1998 to 2017 allowed us to calculate the mineralization rate of the soil organic matter derived from C4 plants grown from 1970 to 1998. We found that the SOC-C4 stock declined in all layers according to a first order kinetics. The mineralization rate obtained over the whole profile (0-28 cm) was remarkably identical in the three tillage treatments, with a mean value *kij* = 0.080 ± 0.001 yr^{-1}. This corresponds to a mean residence time of the active pool of 12.5 ± 0.1 years. This result might appear contradictory with the literature. Two studies (Balesdent *et al*., 1990; Six *et al*., 1998), also using ^{13}C natural abundance methodology, indicated that the MRT of SOC under no tillage was greater than that under full inversion tillage. However, two other studies based on the same technique obtained opposite conclusions. Murage *et al.* (2007) found that the turnover of SOC–C3 in the old ploughed layer of an 11-yr experiment in Canada was unaffected by tillage (NT *vs* CT). Haile-Mariam *et al.* (2008) found no difference (on average) in MRT between no-till and tilled systems in three LTEs in USA, both *in situ* and in laboratory incubations. However, these studies have serious flaws: i) they considered only two dates, an initial and a final point, without providing a diachronic follow-up which reduces uncertainties due to spatial heterogeneity of soils (Fujisaki *et al*., 2017); ii) the initial stock (SOC and SOC4) was not or partially measured and assumptions had to be made to estimate it; iii) there was no statistical analysis of the differences between tillage treatments. Several papers have emphasized the importance of a full diachronic approach with sufficient data points over time to estimate MRT accurately (Bernoux *et al*., 1998; Derrien and Amelung, 2011).

Our results can be compared to those obtained in two incubation studies made previously in the same experiment (Oorts *et al*., 2006; Dimassi *et al*., 2014b). We calculated the mineralization rates relative to a reference, chosen as the layer L1 of the FIT treatment (Fig. 8). Results show that the variations in mineralization rates observed *in situ* between layers and treatments are confirmed by the previous incubation studies, even though the mineralization rates determined *in situ* concern the SOC-C4 formed with maize crops grown before 1998 (at least 14 years from 1970 to 1998) while the mineralization rates calculated in incubation studies concern the whole SOC stock. In another experiment made on a similar soil type, Sauvadet *et al.* (2017) compared a reduced tillage (RT) and a full inversion tillage (CONV) treatment in a 6-yr experiment. They incubated the upper soil layer (0-5 cm) and found that the specific mineralization rate of RT was 62% higher than that of CONV, confirming our results.

4.3 Mineralization rates versus tillage and depth

Our study also revealed that the *in situ* mineralization rate of SOC4 stock varied within layers and tillage treatments with a significant interaction between them. While no significant difference appeared between layers under FIT, differences were found in the reduced tillage treatments: the mineralization rate of the upper layer (L1, ~0-5 cm) in NT and ST was much higher than that observed in the FIT treatment and slightly smaller in lower layers (below 10 cm). The absence of difference between layers in FIT was expected since the annual ploughing mixes the soil and crop residues, homogenizing almost completely their concentrations within the profile. The reduced mineralization rate in layers L3 and L4 of treatments ST and NT can be attributed to an absence of soil disturbance which could result in an increased physical protection (*e.g.* Balesdent *et al.*, 2000) or to smaller C inputs due to the absence of mechanical incorporation of ABG crop residues. It is not possible to disentangle the two processes in these layers. But the absence of difference in mineralization rates in layer L1 between treatments ST and NT, which received similar amounts of crop residues but strongly differed in tillage operations, and the lower mineralization rate in the same layer of the FIT treatment which was tilled intensively, indicate that the first hypothesis has a minor importance. The high correlation found between the mineralization rate and C inputs strongly suggests that the main driver of the mineralization rate is the intensity of C inputs and not the physical soil disturbance.

4.4 Fresh C input as a determinant of C mineralization rate

The amount of C input is known to be an important factor driving the changes in SOC stocks (*e.g.* Luo *et al.*, 2010; Powlson *et al.*, 2011; Li *et al.*, 2018), including the changes due to tillage (Virto *et al.*, 2012). In this study we show that, under field conditions, the amount of C input also drives the mineralization rate (per unit of SOC) of the stabilized organic matter. This conclusion agrees with the results of several other studies. Duong *et al*. (2009) showed that a higher frequency of residue addition increased the C mineralization rate. Gude *et al.* (2012) found that the MRT of SOC was smaller in a high input site than in a low input one. Diochon *et al.* (2016) analyzed the results of a 17-yr LTE comparing a continuous maize, a soybean-maize rotation and a continuous fallow soil and observed that the mineralization rates of the SOC-C3 stocks were correlated with the mean C inputs. Using ^{13}C enriched residues, Sarker *et al.* (2018) showed that crop residue input increased native SOC mineralization *via* positive priming. Cardinael *et al*. (2015) compared the evolution of SOC in a 52-yr LTE maintained bare fallow or receiving applications of wheat straw and found that mineralization rates were much lower in the bare fallow soil.

Therefore, the evolution of SOC is under the control of two opposite processes. The variation in the mineralization rate *vs* C input level is a feedback effect, which could offset the positive effect of increasing C inputs on SOC. In most cases such as in our study, the compensation is incomplete so that the general behavior is a positive correlation between C input and SOC stocks (*e.g*. Liu *et al*., 2014; Li *et al.*, 2018). However, there are a few cases where the compensation can be very important, leading to an opposite relationship. This has been found in situations when N availability is very limiting, such as described by Fontaine *et al*. (2011) or Diochon *et al.* (2016).

The mechanism behind this offset is likely to be the priming effect (PE) due to the addition of fresh organic matter, which has been shown to be a ubiquitous process in all soils (Perveen *et al*., 2019). Several studies made with glucose, cellulose or straw addition indicated that PE increases with the C addition rate (Mary *et al.*, 1993; Guenet *et al.*, 2010; Paterson and Sim, 2013; Liu *et al.*, 2017; Fang *et al*., 2018; Shahzad *et al.,* 2019; Liu *et al*., 2020), and probably until a saturation level which has not been identified because it interacts with the nutrient level in soil (Fontaine *et al*., 2011; Dimassi *et al*., 2014b). In this study, we found that the relationship can be considered to be about linear until a concentration of 5 g C kg^{-1}. Sauvadet *et al.* (2018) found that the PE was similar in the RT and FIT treatments for a given amount of C added, suggesting that the priming is mainly driven by the C addition rate and not by the tillage practices.

On the basis of a laboratory incubation characterizing the PE in the Boigneville experiment in 2012, Dimassi *et al.* (2014b) predicted that "*PE intensity should vary within the soil profile with a maximum in the upper soil layer of NT treatment and a minimum in the lower layer of the same treatment. The mineralization rate of SOM should vary similarly and its mean residence time in the opposite way, suggesting that SOM could reach steady state in upper layer of NT more rapidly than in FIT and even more than in the no-tilled layers*." These predictions are confirmed by the present study.

4.5. Simulation of SOC dynamics using the new mineralization model AMGv3

On the basis of the results obtained using the ^{13}C natural tracing technique, we could propose a new mineralization model which considers the soil and environmental factors already known to influence mineralization rates (Clivot *et al*., 2017, 2019), but also the effect of C input intensity, itself attributed to the priming effect. Applying this model (called AMGv3) to our whole dataset allowed to simulate accurately SOC stocks in most situations, without considering any extra physical protection in the reduced tillage treatments. We conclude that the main effect of a change in tillage on SOC storage is the change in the distribution of C input throughout the profile and the corresponding variation of the PE rather than the change in physical soil disturbance. The exponential function $k_0(I)$ that we propose looks like that proposed by Guenet *et al.* (2018) and allows simulating a saturation effect for high C inputs. It would be interesting to test the equation for grassland soils, which are not tilled and receive high amounts of C inputs, mainly through rhizodeposition.

Overall, the new model was able to reproduce satisfactorily the SOC dynamics in all individual layers and the whole (old) ploughed layer. We noticed that in the last periods (2002-2017) it slightly overestimated SOC stocks in layer L1 and underestimated them in layer L2 of the NT treatment. One possible explanation of these two differences could come from a biased estimate of C input, which could result from transport processes (neglected here): downwards transport of SOC due to bioturbation or liquid phase transport. These processes are difficult to quantify. Including formalisms for these processes (Braakhekke *et al*., 2011; Keyvanshokouhi *et al*., 2019) might further improve the model performance. However, the effects of these processes are expected to be small. In a no-till experiment, Jha *et al.* (2017) compared 6 treatments varying in maize addition rate. After 9 years, they found that SOC stocks in 0-10 cm had increased with addition rate, whereas SOC stock in 10-20 cm was similar in all treatments, indicating that the transport of SOC derived from maize residues was not detectable.

5. Conclusion

This study has demonstrated the consistency of a diachronic approach applied to one of the oldest LTE comparing contrasted tillage treatments. It allowed to make reliable conclusions on the effect of tillage on SOC storage: reduced tillage resulted in SOC storage in the upper soil layers (~0-10 cm) but simultaneously in a SOC decline in the underlying layers (~15-40 cm) and no change in SOC storage compared to conventional tillage over the whole sampling depth (~0-40 cm or ~0-60 cm). It confirms the importance of deep sampling and calculation at equivalent soil mass for comparing tillage treatments and avoiding misinterpretations (Powlson *et al*., 2014). The natural ^{13}C tracing technique applied *in situ* showed that the C mineralization rate and the MRT in each soil layer varied with depth and tillage by a factor of 2.5. This amplitude of variation confirmed the results obtained in previous laboratory studies made on the same experiment. The C mineralization rate appeared to be controlled mainly by the intensity of the C inputs and not by the physical disturbance linked with tillage. Its variation is likely to be caused by the variation in priming effect with C addition rate. Incorporating this effect into the AMG model allowed to improve the simulation of SOC evolution in each soil layer and in the whole (old) ploughed layer without considering any other effect of tillage. Further investigations are required to evaluate the new model AMGv3 on other LTEs comparing treatments with large variation in C inputs, ranging from bare fallow soils to cropping systems with intensive C inputs and grasslands.

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References

Angers, D.A., Eriksen-Hamel, N.S., 2008. Full-inversion tillage and organic carbon distribution in soil profiles: a meta-analysis. Soil Sci. Soc. Am. J. 72, 1370-1374.

Autret, B., Mary, B., Chenu, C., Balabane, M., Girardin, C., *et al.*, 2016. Alternative arable cropping systems: a key to increase soil organic carbon storage? Results from a 16 year field experiment. Agric. Ecosyst. Environ. 232, 150–164.

Balesdent, J., Mariotti, A., Boisgontier, D., 1990. Effect of tillage on soil organic carbon mineralization estimated from 13C abundance in maize fields. J. Soil Sci. 41, 587–596.

Balesdent, J., Chenu, C., Balabane, M., 2000. Relationship of soil organic matter dynamics to physical protection and tillage. Soil Tillage Res. 53, 215-230.

Bernoux, M., Cerri, C.C., Neill, C., de Moraes, J.F.L., 1998. The use of stable carbon isotopes for estimating soil organic matter turnover rates. Geoderma 82, 43–58.

Barré, P., Eglin, T., Christensen, B.T., Ciais, P., *et al.*, 2010. Quantifying and isolating stable soil organic carbon using long-term bare fallow experiments. Biogeosciences 7, 3839–3850.

Blanco-Moure, N., Gracia, R., Bielsa, A.C., López, M.V., 2013. Long-term no-tillage effects on particulate and mineral-associated soil organic matter under rainfed Mediterranean conditions. Soil Use Manag. 29, 250–259.

Bolinder, M.A., Janzen, H.H., Gregorich, E.G., Angers, D.A., VandenBygaart, A.J., 2007. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. Agric. Ecosyst. Environ. 118, 29-42.

Braakhekke, M. C., Beer, C., Hoosbeek, M. R., Reichstein, M., Kruijt, B., Schrumpf, M., Kabat, P., 2011. SOMPROF: A vertically explicit soil organic matter model. Ecol. Model. 222, 1712-1730.

Cardinael, R., Eglin, T., Guenet, B., Neill, C., Houot, S., Chenu, C., 2015. Is priming effect a significant process for long-term SOC dynamics? Analysis of a 52-years old experiment. Biogeochemistry 123, 203–219.

Clapp, C.E., Allmaras, R.R., Layese, M.F., Linden, D.R., Dowdy, R.H., 2000. Soil organic carbon and 13C abundance as related to tillage, crop residue, and nitrogen fertilization under continuous corn management in Minnesota. Soil Tillage Res. 55, 127-142.

Clivot, H., Mary, B., Valé, M., Cohan, J.P., Champolivier, L., *et al*., 2017. Quantifying in situ and modeling net nitrogen mineralization from soil organic matter in arable cropping systems. Soil Biol. Biochem. 111, 44-59.

Clivot, H., Mouny, J.C., Duparque, A., Dinh, J.L. *et al*., 2019. Modeling soil organic carbon evolution in long-term arable experiments with AMG model. Environ. Model. Softw. 118, 99-113.

Costa Junior, C., Corbeels, M., Bernoux, M., Piccolo, M.C., Neto, M.S., et al., 2013. Assessing soil carbon storage rates under no-tillage: Comparing the synchronic and diachronic approaches. Soil Tillage Res. 134, 207–212.

Derrien, D., Amelung, W., 2011. Computing the mean residence time of soil carbon fractions using stable isotopes: impacts of the model framework. Eur. J. Soil Sci. 62, 237–252.

Dikgwatlhe, S.B., Chen, Z.D., Lal, R., Zhang, H.L., Chen, F., 2014. Changes in soil organic carbon and nitrogen as affected by tillage and residue management under wheat–maize cropping system in the North China Plain. Soil Tillage Res. 144, 110–118.

Dimassi, B., Cohan, J.P., Labreuche, J., Mary, B., 2013. Changes in soil carbon and nitrogen following tillage conversion in a long-term experiment in Northern France. Agric. Ecosyst. Environ. 169, 12-20.

Dimassi, B., Mary, B., Wylleman, R., Labreuche, J., Couture, *et al*., 2014a. Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years. Agric. Ecosyst. Environ. 188, 134-146.

Dimassi, B., Mary, B., Perveen, N., Revaillot, S., Cohan, J.P., Fontaine, S., 2014b. Carbon mineralization and priming effect affected by long term tillage. Soil Biol. Biochem. 78, 332-339.

Diochon, A., Gregorich, E.G., Kellman, L., Morrison, M., Ma, B.L., 2016. Greater soil C inputs accelerate loss of C in cropping systems with low N input. Plant Soil 400, 93–105.

Duong, T.T.T., Baumann, K., Marschner, P., 2009. Frequent addition of wheat straw residues to soil enhances carbon mineralization rate. Soil Biol. Biochem. 41, 1475–1482.

Fan, J., McConkey, B., Wang, H., Janzen, H., 2016. Root distribution by depth for temperate agricultural crops. Field Crops Research 189, 68-74.

Fang, Y., Nazaries, L., Singh, B.K., Singh, B.P., 2018. Microbial mechanisms of carbon priming effects revealed during the interaction of crop residue and nutrient inputs in contrasting soils. Glob Chang. Biol. 24, 2775–2790.

Ferchaud, F., Vitte, G., Mary, B., 2016. Changes in soil carbon stocks under perennial and annual bioenergy crops. GCB Bioenergy 8, 290-306.

Fontaine, S., Henault, C., Aamor, A., Bdioui, N., Bloor, J., *et al.*, 2011. Fungi mediate long term sequestration of carbon and nitrogen in soil through their priming effect. Soil Biol. Biochem. 43, 86-96.

Fujisaki, K., Perrin, A.S., Garrica, B., Balesdent, J., Brossard, M., 2017. Soil organic carbon changes after deforestation and agrosystem establishment in Amazonia: An assessment by diachronic approach. Agric. Ecosyst. Environ. 245, 63-73.

Gale, M.R., Grigal, D.F., 1987. Vertical root distributions of northern tree species in relation to successional status. Can. J. Forest Res. 17, 829-834.

Gude, A., Kandeler, E., Gleixner, G., 2012. Input related microbial carbon dynamic of soil organic matter in particle size fractions. Soil Biol. Biochem. 47, 209-219.

Guenet, B., Neill, C., Bardoux, G., Abbadie, L., 2010. Is there a linear relationship between priming effect intensity and the amount of organic matter input? Appl. Soil Ecol. 46, 436-442.

Guenet, B., Camino-Serrano, M., Ciais, P., Tifafi, M., Maignan, F., *et al.*, 2018. Impact of priming on global soil carbon stocks. Glob. Chang. Biol. 24, 1873–1883.

Haile-Mariam, S., Collins, H.P., Wright, S., Paul, E.A., 2008. Fractionation and long-term laboratory incubation to measure soil organic matter dynamics. Soil Sci. Soc. Am. J. 72, 370–378.

Hernanz, J.L., Sanchez-Giron, V., Navarrete, L., 2009. Soil carbon sequestration and stratification in a cereal/leguminous crop rotation with three tillage systems in semiarid conditions. Agric. Ecosyst. Environ. 133, 114–122.

Hiel, M.P., Barbieux, S., Pierreux,J., Olivier, C., Lobet, G., *et al.*, 2018. Impact of crop residue management on crop production and soil chemistry after seven years of crop rotation in temperate climate, loamy soils. PeerJ 6:e4836; peerj.com/articles/4836/

Jha, P., Verma, S., Lal, R., Eidson, C., Dheri, G.S., 2017. Natural 13C abundance and soil carbon dynamics under long-term residue retention in a no-till maize system. Soil Use Manag. 33, 90–97.

Keyvanshokouhi, S., Cornu, S., Lafolie, F., Balesdent, J., Guenet, B., *et al.*, 2019. Effects of soil process formalisms and forcing factors on simulated organic carbon depth-distributions in soils. Sci. Total Environ. 652, 523-537.

Kong, A.Y., Six, J., Bryant, D.C., Denison, R.F., van Kessel, C., 2005. The relationship between carbon input, aggregation, and soil organic carbon stabilization in sustainable cropping systems. Soil Sci. Soc. Am. J. 69,1078–1085.

Labreuche, J., Duval, R., Bureau, S., *et al.*, 2018. Synthesis of a 47-year old field experiment in France, comparing soil tillage techniques in different crop rotations. ISTRO Paris, doi: 10.13140/RG.2.2.16398.00324

Lenth, R., 2019. Emmeans: estimated marginal means, aka least-squares means. R package version 1.3.3. https://CRAN.R-project.org/package=emmeans

Li, Y., Shi, S., Waqas, M.A., Zhou, X., Li, J. *et al.*, 2018. Long-term (≥20 years) application of fertilizers and straw return enhances soil carbon storage: a meta-analysis. Mitig. Adapt. Strateg. Glob. Change 23, 603–619.

Liu, C., Lu, M., Cui, J., Li, B., Fang, C., 2014. Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis. Glob. Chang. Biol. 20, 1366–1381.

Liu, X.J.A., Suna, J., Maua, R.L., Finleya, B.K., Compson, Z.G., 2017. Labile carbon input determines the direction and magnitude of the priming effect. Appl. Soil Ecol. 109, 7–13.

Liu, X.J.A., Finley, B.K., Mau, R.L., Schwartz, E., Dijkstra, P., *et al.*, 2020. The soil priming effect: Consistent across ecosystems, elusive mechanisms. Soil Biol. Biochem. 140, 107617.

López-Fando, C., Pardo, M.T., 2011. Soil carbon storage and stratification under different tillage systems in a semi-arid region. Soil Tillage Res. 111, 224–230.

Luo, Z., Wang, E., Sun, O.J., 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agric. Ecosyst. Environ. 139, 224-231.

Martínez, I., Chervet, A., Weisskopf, P., Sturnyb, W.G., Etanac, A., Stettlerd, M. *et al.*, 2016. Two decades of no-till in the Oberacker long-term field experiment: Part I. Crop yield, soil organic carbon and nutrient distribution in the soil profile. Soil Tillage Res. 163, 141–151.

Mary., B., Fresneau, C., Morel, J.L., Mariotti, A., 1993. C and N cycling during decomposition of root mucilage, roots and glucose in soil. Soil Biol. Biochem. 25, 1005-1014.

Mary, B., Cohan, J.P., Dimassi, B., Recous, S., Laurent, F., 2014. Effet du travail du sol sur les cycles biogéochimiques du carbone et de l’azote. In: "Faut-il travailler le sol ?", Editions QUAE, Versailles, 63-88, ISBN 978-2-8179-0170-1.

Mary, B., Ferchaud, F., Chlebowski, F., Blaszczyk, N., Labreuche, J., 2018. Monitoring SOC changes in the long-term experiment of Boigneville shows no effect of tillage after 47 years. webistem.com/ISTRO2018/output_directory/cd1/data

Meurer, K.H.E., Haddaway, N.R., Bolinder, M.A., Kätterer, T., 2007. Tillage intensity affects total SOC stocks in boreo-temperate regions only in the topsoil—A systematic review using an ESM approach. Earth Science Reviews 177, 613-622.

Murage, E.W., Voroney, P.R., Kay, B.D., Deen, B., Beyaert, R.P., 2007. Dynamics and turnover of soil organic matter as affected by tillage. Soil Sci. Soc. Am. J. 71, 1363–1370.

Olson, K.R., 2013. Soil organic carbon sequestration, storage, retention and loss in U.S. croplands: Issues paper for protocol development. Geoderma 195–196, 201–206.

Olson, K.R., Al-Kaisi, M., Lal, R., Lowery, B., 2014. Examining the paired comparison method approach for determining soil organic carbon sequestration rates. J. Soil Water Cons. 69, 193-197.

Olson, K.R., Al-Kaisi, M.M., 2015. The importance of soil sampling depth for accurate account of soil organic carbon sequestration, storage, retention and loss. Catena 125, 33-37.

Oorts, K., Nicolardot, B., Merckx, R., Richard, G., Boizard, H., 2006. C and N mineralization of undisrupted and disrupted soil from different structural zones of conventional tillage and no-tillage systems in northern France. Soil Biol. Biochem. 38, 2576-2586.

Paterson, E., Sim, A., 2013. Soil-specific response functions of organic matter mineralization to the availability of labile carbon. Global Chang. Biol. 19, 1562–1571.

Paustian, K., Six, J., Elliott, E.T., Hunt, H.W., 2000. Management options for reducing CO_2 emissions from agricultural soils. Biogeochemistry 48, 147–163.

Perveen, N., Barot, S., Maire, V. *et al.*, 2019. Universality of priming effect: An analysis using thirty five soils with contrasted properties sampled from five continents. Soil Biol. Biochem. 134, 162–171.

Piccoli, I., Chiarini, F., Carletti, P., Furlan, L., Lazzaro, B., 2016. Disentangling the effects of conservation agriculture practices on the vertical distribution of soil organic carbon. Evidence of poor carbon sequestration in North- Eastern Italy. Agric. Ecosyst. Environ. 230, 68–78.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., R Core Team, 2018. nlme: Linear and nonlinear mixed effects models. R package version 3.1-137, https://CRAN.R-project.org/package=nlme

Pittelkow, C.M., Liang, X., Linquist, B.A., van Groenigen, K.J., Lee, J., Lundy, M.E. *et al.*, 2015. Productivity limits and potentials of the principles of conservation agriculture. Nature 517, 365-368.

Powlson, D.S., Whitmore, A.P., Goulding, K.W.T., 2011. Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. Eur. J. Soil Sci.. 62, 42-55.

Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., *et al.*, 2014. Limited potential of no-till agriculture for climate change mitigation. Nature Climate Change, 4, 678-683. doi: 10.1038/nclimate2292

Qin, R., Stamp, P., Richner, W., 2004. Impact of tillage on root systems of winter wheat. Agron. J. 96, 1523–1530.

Qin, R., Stamp, P., Richner, W., 2006. Impact of tillage on maize rooting in a Cambisol and Luvisol in Switzerland. Soil Tillage Res. 85, 50–61.

R Core Team, 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Saffih-Hdadi, K., Mary, B., 2008. Modeling consequences of straw residues export on soil organic carbon. Soil Biol. Biochem. 40, 594–607.

Sarker, J.R., Singh, B.P., Cowie, A.L., Fang, Y., Collins, D., *et al.*, 2018. Carbon and nutrient mineralisation dynamics in aggregate-size classes from different tillage systems after input of canola and wheat residues. Soil Biol. Biochem. 116, 22–38.

Sauvadet, M., Lashermes, G., Alavoine, G., Recous, S., Chauvat, M., *et al.*, 2018. High carbon use efficiency and low priming effect promote soil C stabilization under reduced tillage. Soil Biol. Biochem. 123, 64-73.

Shahzad, T., Anwar, F., Hussain, S., *et al.*, 2019. Carbon dynamics in surface and deep soil in response to increasing litter addition rates in an agro-ecosystem. Geoderma 333, 1-9.

Singh, P., Heikkinen, J., Ketoja, E., Nuutinen, V., Palojärvi, A., *et al*., 2015. Tillage and crop residue management methods had minor effects on the stock and stabilization of topsoil carbon in a 30-year field experiment. Sci. Total Environ. 518–519, 337–344

Six, J., Elliott, E.T., Paustian, K., Doran, J.W., 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Sci. Soc. Am. J. 62, 1367-1377.

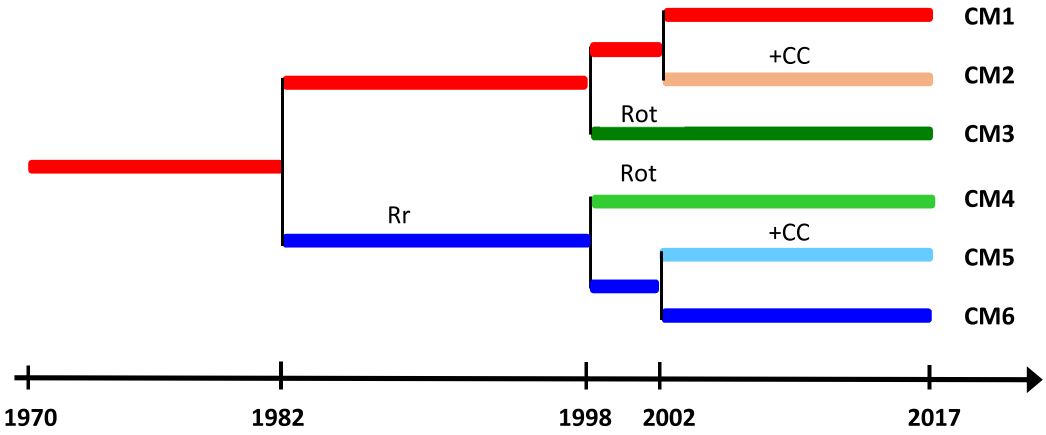
Six, J., Elliott, E.T., Paustian, K., 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci. Soc. Am. J. 63, 1350–1358.

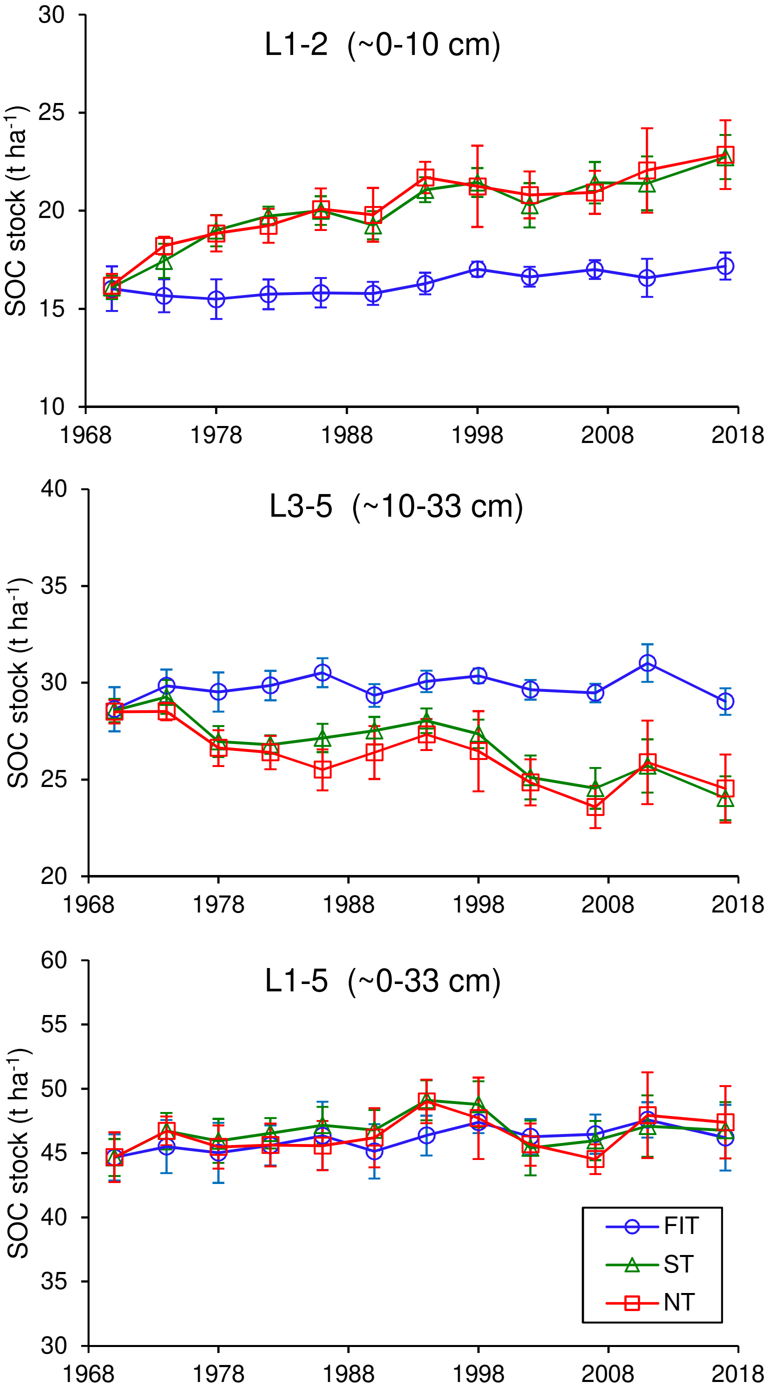
UNEP, 2013. The Emissions Gap Report 2013. United Nations Environment Programme. http://web.unep.org/sites/default/files/EGR2013/EmissionsGapReport_2013_high-res.pdf

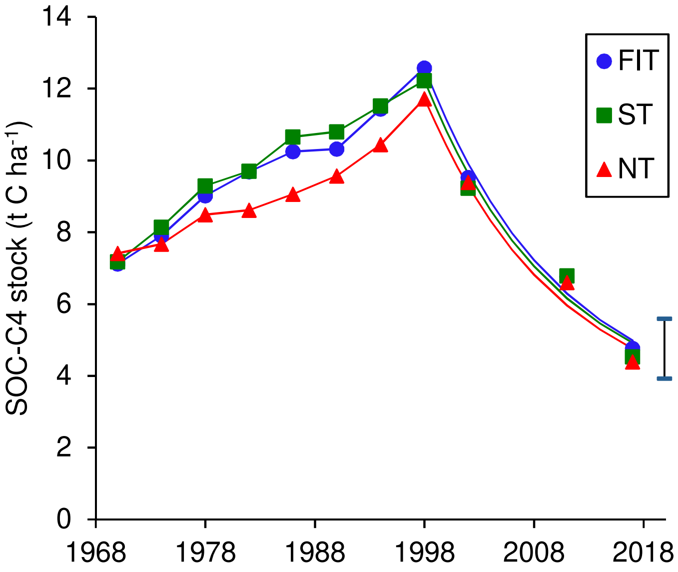
Valboa, G., Lagomarsino, A., Brandi, G., Agnelli, A.E., Simoncini, S., 2015. Long-term variations in soil organic matter under different tillage intensities. Soil Tillage Res. 154, 126-135.

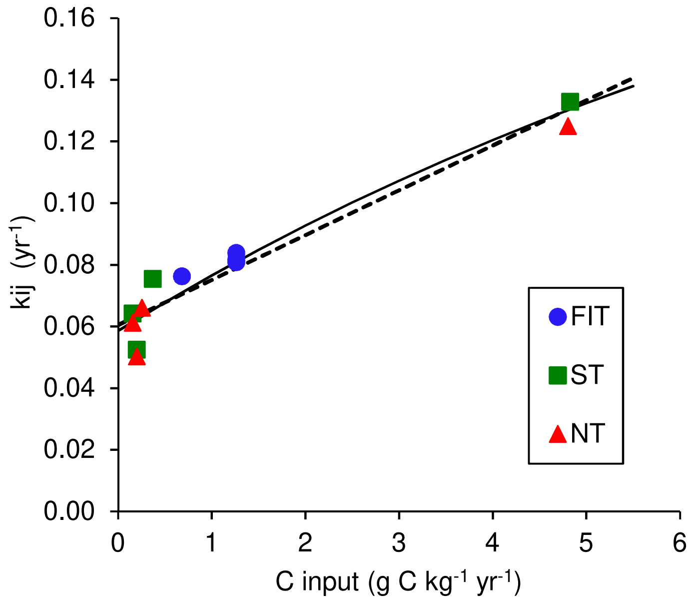
Virto, I., Barré, P., Burlot, A., Chenu, C., 2012. Carbon input differences as the main factor explaining the variability in soil organic C storage in no-tilled compared to inversion tilled agrosystems. Biogeochemistry 108, 17-26.

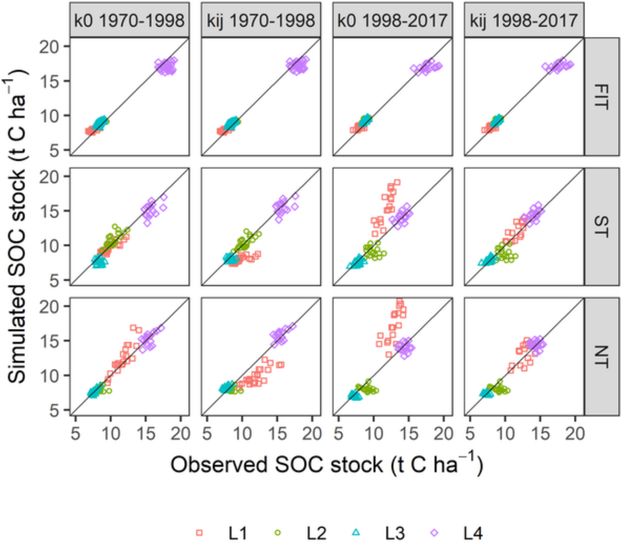
Wendt, J.W., Hauser, S., 2013. An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. Eur. J. Soil Sci. 64, 58–65.

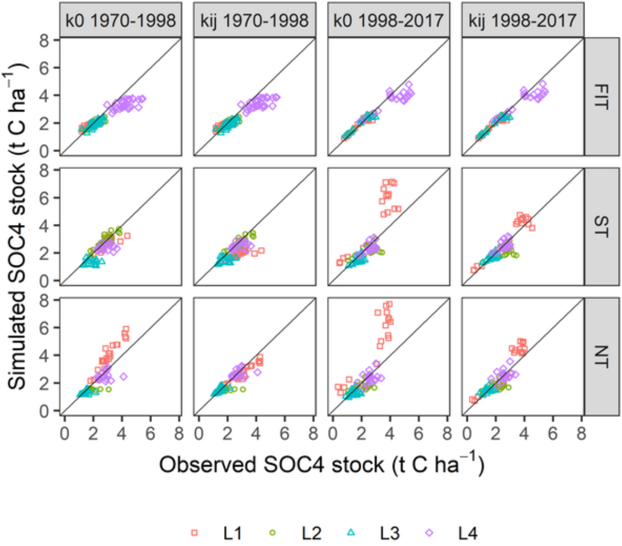

CM1
+CC
CM2
Rot
CM3
Rot
CM4
Rr
+CC
CM5
CM6
1970
1982
1998
2002
2017

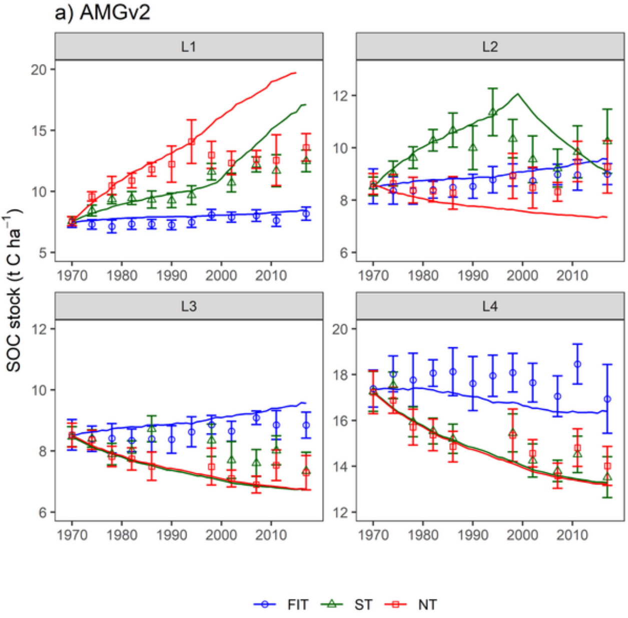

L1-2 (~0-10 cm)
SOC stock (t ha^{-1})
30
25
20
15
10
1968
1978
1988
1998
2008
2018
L3-5 (~10-33 cm)
SOC stock (t ha^{-1})
40
35
30
25
20
1968
1978
1988
1998
2008
2018
L1-5 (~0-33 cm)
SOC stock (t ha^{-1})
60
55
50
45
40
35
30
1968
1978
1988
1998
2008
2018
FIT
ST
NT

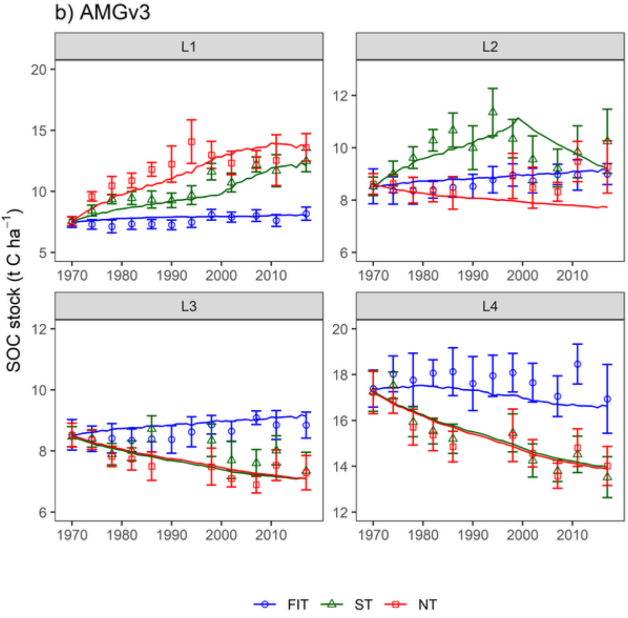

SOC-C4 stock (t C ha^{-1})
14
12
10
8
6
4
2
0
1968
1978
1988
1998
2008
2018
FIT
ST
NT

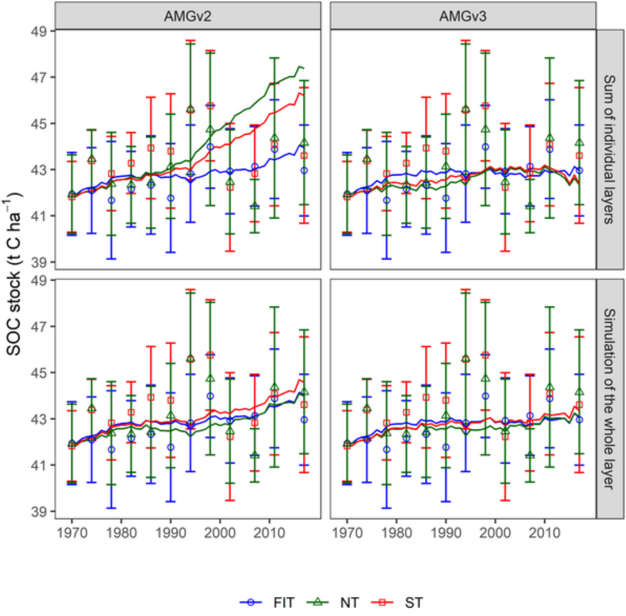

0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
kij (yr-1)
0
1
2
3
4
5
6
C input (g C kg-1 yr-1)
FIT
ST
NT


k0 1970-1998
kij 1970-1998
k0 1998-2017
kij 1998-2017
FIT
ST
NT
Simulated SOC stock (t C ha^{-1})
Observed SOC stock (t C ha^{-1})
5
10
15
20
L1
L2
L3
L4


k0 1970-1998
kij 1970-1998
k0 1998-2017
kij 1998-2017
FIT
ST
NT
Simulated SOC4 stock (t C ha^{-1})
Observed SOC4 stock (t C ha^{-1})
0
2
4
6
8
L1
L2
L3
L4


a) AMGv2
L1
L2
L3
L4
SOC stock (t C ha^{-1})
20
15
10
5
12
10
8
6
20
18
16
14
12
1970
1980
1990
2000
2010
FIT
ST
NT

b) AMGv3
L1
L2
L3
L4
SOC stock (t C ha^{-1})
20
15
10
5
12
10
8
6
12
10
8
6
20
18
16
14
12
1970
1980
1990
2000
2010
FIT
ST
NT


AMGv2
AMGv3
Sum of individual layers
Simulation of the whole layer
SOC stock (t C ha^{-1})
49
47
45
43
41
39
1970
1980
1990
2000
2010
FIT
NT
ST

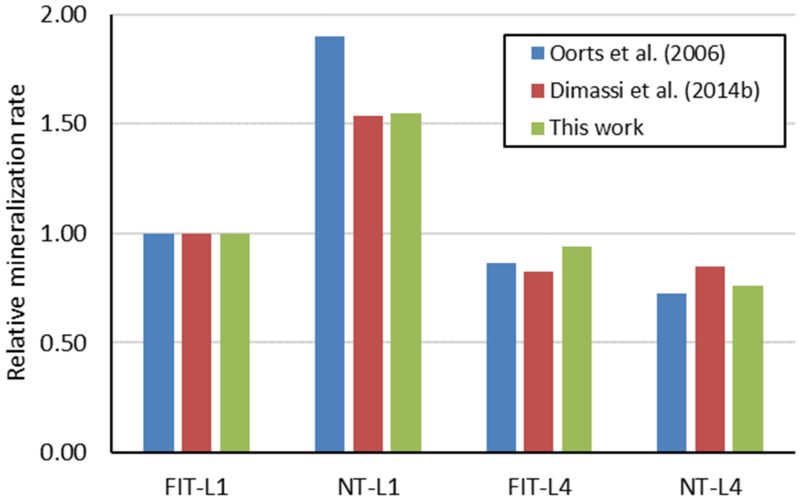

2.00
1.50
1.00
0.50
0.00
Relative mineralization rate
Oorts et al. (2006)
Dimassi et al. (2014b)
This work
FIT-L1
NT-L1
FIT-L4
NT-L4

Table 1. SOC concentration and cumulative SOC stock per soil layer and the three tillage treatments in 2017 (mean of the six crop management treatments). Values in parentheses are the standard deviations. Letters indicate significant differences between tillage treatments ($p < 0.05$).

Layer	Soil mass (t ha^{-1})	Depth (cm)	C concentration (g kg^{-1})			Layer	Soil mass (t ha^{-1})	Depth (cm)	Cumulative SOC stock (t C ha^{-1})		
			FIT	ST	NT				FIT	ST	NT
L1	700	~ 0-5	**11.78** (0.91) c	**18.04** (1.25) b	**19.67** (1.68) a	L1	700	~ 0-5	**8.18** (0.64) c	**12.49** (0.89) b	**13.60** (1.13) a
L2	800	~ 5-10	**11.28** (0.71) b	**12.80** (1.53) a	**11.59** (1.27) b	L1-2	1500	~ 0-10	**17.18** (1.11) b	**22.74** (1.70) a	**22.87** (1.74) a
L3	800	~ 10-15	**11.07** (0.67) a	**9.19** (0.75) b	**9.10** (0.67) b	L1-3	2300	~ 0-15	**26.02** (1.45) b	**30.08** (2.24) a	**30.15** (2.09) a
L4	1760	~ 15-28	**9.61** (1.02) a	**7.68** (0.52) b	**7.96** (0.49) b	L1-4	4060	~ 0-28	**42.96** (2.53) a	**43.61** (2.93) a	**44.17** (2.68) a
L5	540	~ 28-33	**6.03** (1.06) a	**5.83** (0.56) a	**5.96** (0.38) a	L1-5	4600	~ 0-33	**46.20** (2.84) a	**46.76** (3.08) a	**47.40** (2.75) a
L6	4000	~ 33-60	**4.75** (0.69) a	**4.81** (0.58) a	**4.89** (0.52) a	L1-6	8600	~ 0-60	**65.21** (4.96) a	**65.99** (4.27) a	**66.93** (3.66) a

Table 2. Quality of fit (RRMSE = relative RMSE) and mineralization rate constants (*kij*) calculated during the decay of SOC-C4 stocks in treatments CM3 and CM4, per soil layer and tillage treatment. Values in parentheses are the standard deviations. Uppercase letters indicate significant differences between layers ($p < 0.05$). Lowercase letters indicate significant differences between tillage treatments ($p < 0.05$).

Layer	Depth (cm)	Tillage treatment											
		FIT				ST				NT			
		RRMSE	*kij* *(yr^{-1})*			RRMSE	*kij* *(yr^{-1})*			RRMSE	*kij* *(yr^{-1})*		
L1	~ 0-5	0.054	**0.081** (0.018)	A	b	0.168	**0.133** (0.025)	A	a	0.213	**0.125** (0.028)	A	a
L2	~ 5-10	0.055	**0.082** (0.016)	A	a	0.067	**0.075** (0.013)	B	a	0.117	**0.066** (0.015)	B	a
L3	~ 10-15	0.056	**0.084** (0.019)	A	a	0.105	**0.053** (0.017)	C	b	0.115	**0.050** (0.004)	B	b
L4	~ 15-28	0.072	**0.076** (0.016)	A	a	0.126	**0.064** (0.030)	BC	a	0.120	**0.061** (0.011)	B	a
L1-4	~ 0-28	0.059	**0.080** (0.017)		a	0.068	**0.079** (0.019)		a	0.113	**0.080** (0.010)		a

Table 3. C inputs per soil layer: mean values (t C ha^{-1} yr^{-1}) calculated over the periods 1970-1998 and 1998-2017. Values in parenthesis (sd) are the standard deviations between crop management treatments. Calculations are based on the method of Bolinder *et al.* (2003) with non allometric root:shoot ratio, as described by Clivot *et al.* (2019).

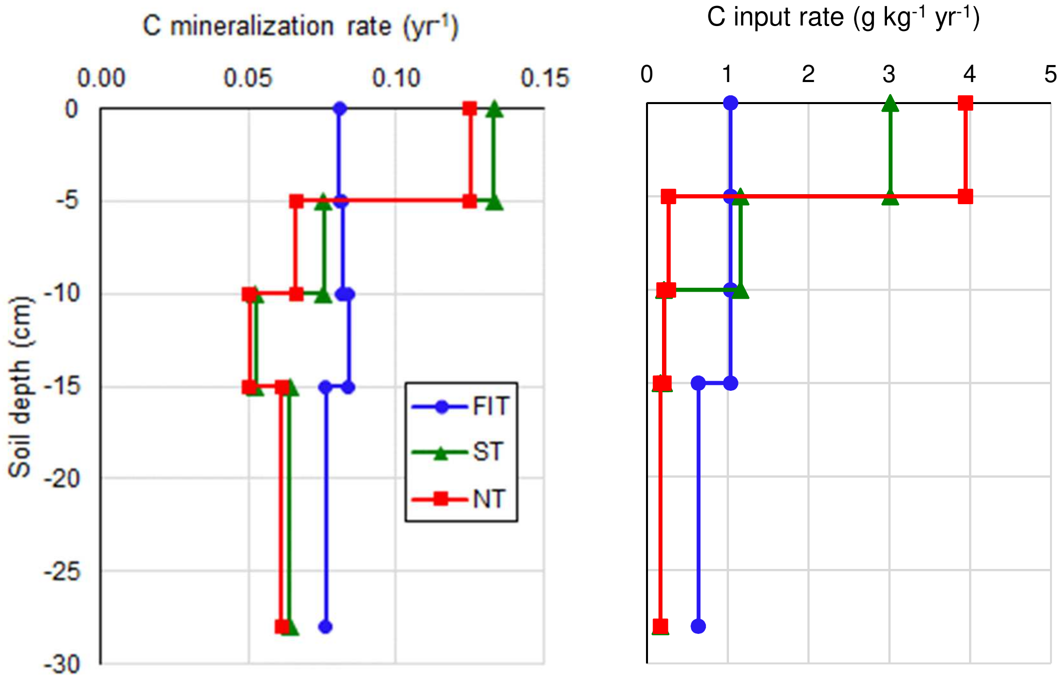
			C inputs (t C ha^{-1} yr^{-1})					
	Layer	Depth	FIT		ST		NT	
		(cm)	mean	sd	mean	sd	mean	sd
a) Period 1970-1998								
	L1	~ 0-5	0.61	(0.10)	1.20	(0.39)	2.33	(0.37)
	L2	~ 5-10	0.70	(0.11)	1.38	(0.08)	0.22	(0.03)
	L3	~ 10-15	0.70	(0.11)	0.17	(0.02)	0.17	(0.02)
	L4	~ 15-28	1.06	(0.14)	0.31	(0.04)	0.31	(0.04)
	L1-4	**~ 0-28**	**3.06**	**(0.45)**	**3.06**	**(0.52)**	**3.03**	**(0.46)**
	L1-5	~ 0-33	3.13	(0.46)	3.12	(0.53)	3.09	(0.47)
b) Period 1998-2017								
	L1	~ 0-5	0.88	(0.12)	3.38	(0.53)	3.36	(0.45)
	L2	~ 5-10	1.01	(0.14)	0.30	(0.04)	0.20	(0.04)
	L3	~ 10-15	1.01	(0.14)	0.16	(0.03)	0.16	(0.03)
	L4	~ 15-28	1.20	(0.16)	0.27	(0.06)	0.27	(0.06)
	L1-4	**~ 0-28**	**4.10**	**(0.56)**	**4.11**	**(0.67)**	**4.00**	**(0.59)**
	L1-5	~ 0-33	4.16	(0.58)	4.16	(0.68)	4.05	(0.60)

Table 4. Statistical evaluation of AMG model for predicting SOC and SOC4 stocks in all situations (6 crop managements x 11 dates) for each layer (L1-L4) and each tillage system (FIT, NT or NT). MD = mean difference (t C ha^{-1}); RMSE = root mean square error (t C ha^{-1}).

Mineralization rate model *	Layer	Depth cm	SOC						SOC4					
			MD			RMSE			MD			RMSE		
			FIT	ST	NT	FIT	ST	NT	FIT	ST	NT	FIT	ST	NT
k_0	L1	~ 0-5	0.42	1.32	2.94	0.54	2.41	4.15	-0.03	0.44	1.81	0.25	1.07	2.21
	L2	~ 5-10	0.37	0.29	-1.11	0.45	1.04	1.41	-0.19	-0.01	-0.52	0.30	0.39	0.66
	L3	~ 10-15	0.45	-0.78	-0.23	0.51	0.93	0.45	-0.18	-0.62	-0.28	0.28	0.70	0.38
	L4	~ 15-28	-0.99	-0.57	-0.59	1.31	0.99	0.99	-1.01	-0.61	-0.53	1.15	0.73	0.70
	L1-4 **	~ 0-28	0.25	0.01	1.09	1.16	2.40	2.81	-1.42	-0.86	0.47	1.80	1.29	1.19
kij	L1	~ 0-5	0.42	-1.23	-1.30	0.54	1.60	1.93	-0.03	-0.60	0.06	0.25	0.84	0.56
	L2	~ 5-10	0.34	-0.24	-1.09	0.44	1.03	1.40	-0.20	-0.23	-0.52	0.31	0.48	0.65
	L3	~ 10-15	0.37	-0.25	0.41	0.44	0.52	0.53	-0.21	-0.41	-0.04	0.30	0.51	0.22
	L4	~ 15-28	-0.76	-0.12	0.06	1.13	0.83	0.75	-0.92	-0.44	-0.28	1.06	0.58	0.50
	L1-4 **	~ 0-28	0.38	-2.08	-1.83	1.18	2.83	2.78	-1.37	-1.75	-0.78	1.76	2.01	1.27
$k_0 (I)$	L1	~ 0-5	0.30	-0.50	-0.40	0.48	0.86	1.40	-0.09	-0.30	0.44	0.30	0.53	0.67
	L2	~ 5-10	0.23	-0.16	-0.78	0.39	0.88	1.13	-0.25	-0.20	-0.39	0.37	0.43	0.54
	L3	~ 10-15	0.31	-0.46	0.09	0.40	0.66	0.37	-0.24	-0.50	-0.16	0.34	0.59	0.29
	L4	~ 15-28	-0.76	0.08	0.05	1.15	0.83	0.74	-0.92	-0.37	-0.29	1.07	0.52	0.51
	L1-4 **	~ 0-28	0.08	-1.29	-0.95	1.32	2.36	2.25	-1.50	-1.43	-0.41	1.94	1.75	1.05

* k_0 = standard mineralization rate (model AMGv2); *kij* = fixed mineralization rates per layer and treatment (Table 2); $k_0 (I)$ = mineralization rate varying with C input (Eq. 5) (model AMGv3).

** Sum of individual simulations of layers L1, L2, L3 and L4.


C mineralization rate (yr^{-1})
0.00
0.05
0.10
0.15
0
-5
-10
-15
-20
-25
-30
Soil depth (cm)
FIT
ST
NT
C input rate (g kg^{-1} yr^{-1})
0
1
2
3
4
5