



## Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years



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### ARTICLE INFO

#### Article history:

Received 20 January 2014

Accepted 6 February 2014

Available online 20 March 2014

#### Keywords:

Soil organic carbon

SOC

Long-term

Dynamics

Crop management

Crop production

Tillage

### ABSTRACT

Although numerous studies have been conducted on the effect of tillage on soil organic carbon (SOC), there is still no consensus on the importance of sequestration which can be expected from reduced tillage. Most studies have used a synchronic approach in fields or long-term experiments which were often poorly characterized with respect to initial conditions. In this paper, we used a diachronic approach to quantify SOC changes in a 41 years experiment comparing no-till (NT), shallow till (ST) and full inversion tillage (FIT) combined with crop managements (residues removal, rotation and catch crops). It included SOC measurements at time 0 and every 4 years, calculations at equivalent soil mass within or below the old ploughed layer. Results show that tillage or crop management had no significant effect on SOC stocks after 41 years both in the old ploughed layer (ca. 0–28 cm) and deeper (ca. 0–58 cm). Tillage had no effect on crop yields and residues. In the reduced tillage treatments (ST and NT), SOC accumulated in the surface layer (0–10 cm), reaching a plateau after 24 years but declined continuously in the lower layer (10–28 cm) at a rate of 0.42–0.44% yr<sup>-1</sup>. The difference in SOC stocks (ST or NT minus FIT) over the old ploughed layer followed a non-monotonic pattern over time. Reduced tillage caused a rapid SOC sequestration during the first 4 years which remained more or less constant (mean = 2.17 and 1.31 t ha<sup>-1</sup>, resp.) during the next 24 years and disappeared after 28 years. The drop was attributed to the higher water balance recorded during years 24–28. In the reduced tillage treatments, the changes in SOC over time were negatively correlated with the water balance, indicating that sequestration rate was positive in dry periods and negative in wet conditions. This study highlights the interest of diachronic approaches to understand the effect of tillage and its interaction with environmental and management factors.

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## 1. Introduction

The atmospheric carbon dioxide concentration has rapidly and substantially risen by about 100 ppm corresponding to 36% over the last 250 years, reaching 391 ppm in 2011 (IPCC, 2013). Changing the agricultural practices represents one of the low cost solutions proposed to mitigate this increase through carbon sequestration by increasing carbon sinks in soil or vegetation and/or reducing CO<sub>2</sub> emission (Smith et al., 2008). In arable soils, the improved practices include crop residues management, establishment of cover crops and reduced tillage which may extend to no-till (Smith et al.,

1998, 2008; Lal, 2004, 2011; Powlson et al., 2012). There is a general agreement to conclude that soil organic carbon (SOC) stocks increase when crop residues are returned rather than removed (e.g. Powlson et al., 2011a) or when catch crops are grown regularly (Constantin et al., 2010; Justes et al., 2012). Although reduced tillage may favor C sequestration, there is no consensus on the importance of this process in continuously no-tilled systems (NT) due to the large variability in measurements (Ogle et al., 2012). Applying NT instead of conventional tillage (CT) is recommended to maintain or increase SOC (West and Post, 2002; Lal, 2004) and mitigate CO<sub>2</sub> emissions (Powlson et al., 2011b). These expected benefits, together with the reduction in cultivation costs, have contributed to the expansion of NT during the last three decades around the world especially in America and Australia.

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Despite the great effort made to quantify the benefit of no-till on SOC stocks, hundreds of studies and several meta-analyses, there is still a controversy. In the 90s and early 2000, many studies suggested that NT generally results in C sequestration, but this conclusion has been questioned later with more rigorous studies and meta-analyses. Concomitantly, the C sequestration potential has been revised downwards. Smith et al., 1998 estimated the potential in the European Union at 0.73% per year following a complete conversion of arable land management into NT, achieving 37% of SOC after 50 years. The first meta-analysis conducted by West and Post, 2002 examined 67 long-term agricultural experiments and concluded that conversion of CT to NT can sequester  $0.57 \pm 0.14 \text{ t Ch}^{-1} \text{ yr}^{-1}$  with maximum sequestration rates occurring between 5 and 10 years. Assuming that the equilibrium was obtained in 20 years, this would result in a 28% increase in SOC. Ogle et al., 2005 found that the conversion could increase SOC storage by 10% and 16% over 20 years in temperate dry and temperate moist climates, respectively. More recently, Smith et al., 2008 revised again the potential downwards to 3–12% of SOC for cool dry and cool moist, both for improved tillage and residue management.

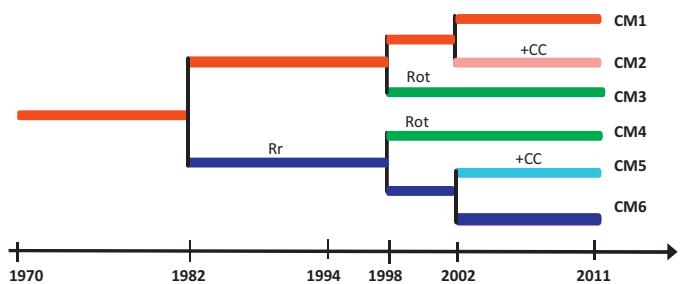
However, some authors such as Baker et al., 2007 pointed out that sampling protocol, particularly insufficient depth sampling, may have biased the results. Three recent meta-analyses (Angers and Eriksen-Hamel, 2008; Luo et al., 2010a; Virtó et al., 2012) have been conducted, selecting published data on the following basis: contrasted tillage treatments (NT versus FIT), same crop management, measured bulk density, calculation at equivalent soil mass (ESM), long duration (>5 years), deep sampling ( $\geq 30 \text{ cm}$ ) and information on C inputs. They found that the mean C sequestration rate (NT–FIT) was 4.9, –0.2 and  $3.4 \text{ t Ch}^{-1}$  respectively after 13–16 years of change in tillage. Virtó et al., 2012 showed that the main factor explaining the variability was the amount of C input to soil every year and did not find any effect of tillage duration. Angers and Eriksen-Hamel, 2008 found a weak correlation with duration but the correlation was only due to one point. The quasi absence of duration effect is surprising and contradictory with a constant sequestration rate. Indeed very few studies have looked at the dynamics of SOC throughout time. Most studies have made a synchronic approach, not a diachronic one. Neto et al., 2010 pointed out the drawback of synchronic studies: “As with paired plots where there is no real repetition of the treatments, the non-homogeneity of the initial soil conditions can create a serious bias in synchronic studies”. It is therefore essential to analyze the tillage effects throughout time in long-term experiments including accurate measurements made at time 0.

In this paper, we examine the effect of soil tillage on SOC in a long-term experiment which is one the oldest tillage experiment including a full diachronic analysis. We enlarged considerably the database and improved the calculations compared to a previous study reported on this experiment (Metay et al., 2009). The originality of our approach consisted in (i) following the SOC distribution throughout the soil profile and its evolution throughout time over 41 years in three contrasted tillage treatments, (ii) analyzing the interaction between soil tillage and other cropping practices (residues, rotation and catch crops) and climatic factors. It is consistent with IPCC recommendations and recent meta-analyses, since it includes measurements of bulk density and SOC contents at depth greater than 30 cm, and calculations on ESM basis using two calculation methods.

## 2. Materials and methods

### 2.1. Experimental design

The ongoing long-term experiment on soil tillage, referred to as Experiment A, was established in 1970 at the experimental



**Fig. 1.** Diagram showing the six crop managements (CM1–CM6) introduced successively in Experiment A since 1970. The symbols indicate the changes in crop management compared to the initial management (CM1): Rr = crop residues removed (1982–1994); Rot = new rotation (wheat/barley/sugarbeet/pea); CC = catch crops.

station of Arvalis-Institut du Végétal at Boigneville in Northern France ( $48^{\circ}19'37''\text{N}$ ,  $2^{\circ}22'56''\text{E}$ ). The soil is a Haplic Luvisol developed on loess; its main characteristics are given in Table 1. The average annual temperature and precipitation over the 41 years study (1970–2011) are  $10.9^{\circ}\text{C}$  and 628 mm, respectively. Before 1970, the field had been under cultivation for many years and had been mouldboard ploughed annually. In 1970, at the onset of the experiment, the soil was ploughed at a depth of ca. 28 cm.

Three tillage treatments were established in the autumn 1970: no-till (NT), shallow tillage (ST) and full inversion tillage (FIT). From 1971 onwards, the ploughing depth was reduced progressively starting from about 25 cm and ending at about 22 cm, i.e. shallower than the previous ploughing depth which enabled to define a constant soil mass over time (see below). In all treatments, wheat straw and maize stalks were chopped and spread after harvest. 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 favor 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). In the NT treatment, tillage occurred only at sowing.

The experiment was carried out in a randomized block system with four blocks (Appendix 1). In addition to tillage treatments, six crop managements were established progressively over time during four periods over 41 years (Fig. 1). During the first period (1970–1982), all plots were cropped with a maize/winter wheat rotation. All crop residues were returned to soil: this defines the first crop management (CM1) which was continued until 2011. 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 years rotation (winter wheat/barley/sugarbeet/pea) yielding two new crop managements (CM3 and CM4), CM3 deriving from CM1 and CM4 deriving from CM6. During the fourth period (2002–2011), plots in blocks 1 and 2, 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 average N fertilization was 189, 168, 135 and  $81 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  for wheat, maize, sugarbeet and spring barley respectively. Maize was irrigated one to three times during summer from 2000 onwards, at the same rate on all treatments (average rate =  $106 \text{ mm yr}^{-1}$ ). The meteorological data are given in Appendix 2.

**Table 1**

Physical and chemical soil characteristics of Experiment A (measured in 2002).

Tillage treatment	Layer (cm)	Clay <2 µm (g kg⁻¹)	Fine silt 2–20 µm (g kg⁻¹)	Coarse silt 20–50 µm (g kg⁻¹)	Fine sand 50–200 µm (g kg⁻¹)	Coarse sand 200–2000 µm (g kg⁻¹)	CaCO₃ (g kg⁻¹)	pH water	CEC (cmol kg⁻¹)
FIT	0–28	246	289	356	55	20	<1	6.9	12.9
	28–40	305	289	325	40	11	<1	7.4	12.9
	40–60	325	282	332	29	5	<1	7.5	14.1
	60–80	326	288	329	32	4	nd	7.7	14.8
ST	0–28	237	295	362	56	23	<1	6.7	13.1
	28–40	280	279	362	45	10	<1	7.2	12.4
	40–60	315	283	342	33	6	<1	7.5	12.8
	60–80	335	282	331	28	5	nd	7.6	13.2
NT	0–28	234	292	361	57	24	<1	6.6	12.7
	28–40	287	283	344	45	17	<1	6.9	12.6
	40–60	319	291	325	34	11	<1	7.1	13.3
	60–80	343	282	319	32	8	nd	7.0	14.1

## 2.2. Soil sampling

Soil sampling strategy was designed to calculate SOC stocks on ESM basis over a depth greater than the deeper current tillage. One particular feature of the experiment was to measure the old ploughing depth (called Y in the following text) at each sampling date. The identification of Y (cm) was performed by detecting changes in soil color and structure on the soil cores. We assume that there was no erosion (due to good drainage, very weak slope of the field and moderate rainfall), so that the soil mass must be constant over the depth 0–Y.

Soil samples were collected with a ca. 4 years frequency in 1970, 1974, 1978, 1982, 1986, 1990, 1994, 1998, 2002, 2007 and 2011, using two methods. The first one, used at each sampling date, consisted in opening four soil trenches (about 50 × 50 × 50 cm) per plot. Three soil samples were taken from two trench walls down to 5 cm below the old ploughing depth using a flat blade. They were divided into several layers (5 cm thick) and gathered together for each layer. Y depth was systematically measured on these samples, with eight replicates per soil trench. In 2011, additional measurements were realized with a second method using a hydraulic gauge (Humax drilling gauge, Switzerland) to pull out soil cores of 8 cm diameter and 20 cm height, inserted in plastic tubes. The soil was sampled down to 60 cm and each core was divided into six layers (0–5, 5–10, 10–15, 15–Y, Y–40 and 40–60 cm). Four soil cores were collected in each plot and two of them were gathered, giving two sub-replicates which were analyzed separately.

## 2.3. Soil analysis

Coarse residues and roots present in the fresh soil cores were first removed by handpicking. Soil samples were oven dried at 35 °C for 48 h, crushed to pass through a 2 mm sieve and finely ground with a ball mill (Retsch, Germany) before carbon (and nitrogen) analysis. Two methods were used for C analysis: Anne method (1970–2007) and Dumas method (dry combustion) (1970–2011). Anne method (AFNOR X31-109) consists in a wet digestion and is very close to Walkley and Black method. 2742 soil samples were collected during the 41 years experiment, air dried, stored and further analyzed, producing a set of 8950 analyses of total C and N.

Bulk densities were first measured in 1971. No significant differences were found between tillage treatments and blocks. Therefore the mean values of each layer were used to calculate the “reference” soil mass (see below). During the first and second periods (1971–1998), bulk densities were measured at various occasions in 1972, 1973, 1974, 1975, 1978, 1983 and 1990, using three methods: membrane densitometer, cylinder and gammameter. Statistical

analysis indicated that there was no significant difference between methods and throughout time, but a significant effect of soil tillage and depth. Therefore the values averaged over time and methods (varying according to depth and tillage) were used at each sampling time to calculate SOC stocks from 1974 to 1998. From 2002 until 2011, bulk densities were determined simultaneously to soil sampling in all plots over the whole profile, using the cylinder method in 2001 and a dual gamma probe (LPC-INRA, Angers, France) in 2007 and 2011 with eight replicates per layer. Bulk densities in the 40–60 cm layer were determined by weighing all soil cores (8 cm diameter) sampled in this layer. A set of 2050 measurements of bulk density was performed in 2011. All measured data (bulk densities, Y depths, C and N concentrations,  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  and POM) were inserted into a database (PostgreSQL) from which statistical analyses and calculations were made. Only total SOC measurements are presented in this paper.

## 2.4. Crop yields and residues

Grain yield was determined every year in each plot on the grain collected with the harvester machine. The harvest index (ratio of grain to total aerial dry matter) was measured on subplots (1 m<sup>2</sup> size) at several dates. The mean values were 0.54 ± 0.02, 0.51 ± 0.02, 0.57 ± 0.02 and 0.48 ± 0.02 for maize, winter wheat, spring barley and spring pea, respectively. They were used to calculate the total amount of aerial dry matter and therefore the amount of above ground crop residues returned to soil after harvest.

## 2.5. Calculation of soil mass and SOC stocks

We used the ESM method for comparing SOC stocks of the various treatments. Two correction methods were performed to obtain the ESM basis at each date, detailed in Dimassi et al., 2013. Soil mass in the layer 0–Y is calculated as:

$$M(Y) = 10 \sum_{j=1}^Y \rho(j) \quad (1)$$

where M(Y) is the mass of dry soil (t ha<sup>-1</sup>), j the soil depth (mm) and  $\rho(j)$  the bulk density (g cm<sup>-3</sup>) of layer j. As mentioned earlier, this soil mass must be constant and equal to the initial soil mass, called reference soil mass ( $M_R$ ):

$$M_R = 10 \sum_{j=1}^{Y_R} \rho_R(j) \quad (2)$$

The measurements of the old ploughing depth Y and bulk densities made at the start of experiment in 1971 allowed us to

determine  $Y_R = 280 \pm 6 \text{ mm}$  and  $M_R = 4060 \pm 90 \text{ t ha}^{-1}$ . The measurements of  $Y$  and  $\rho(j)$  made at each sampling date were used to calculate  $M(Y)$ . Since  $M(Y)$  was not strictly equal to  $M_R$ , we used two correction methods to obtain a constant ESM. The first method assumed that the measured  $Y_m$  values were true whereas bulk densities  $\rho_m(j)$  were not. A correction factor  $\lambda$  was applied to the bulk density of each layer in order to match the same reference mass:

$$\lambda = \frac{M_R}{M(Y_m)} \quad (3)$$

and

$$\rho_c(j) = \lambda \rho_m(j) \quad (4)$$

where  $\rho_c(j)$  is the corrected bulk density ( $\text{g cm}^{-3}$ ) of layer  $j$  at each date.

The corresponding calculation of SOC stock ( $\text{SOC}_1$ , in  $\text{t ha}^{-1}$ ) is:

$$\text{SOC}_1(Y) = \sum_{j=1}^{Y_m} \rho_c(j) \cdot C(j) \quad (5)$$

where  $C(j)$  is the C concentration in layer  $j$  ( $\text{g kg}^{-1}$  dry soil at  $105^\circ\text{C}$ ).

The second method assumed that the measured bulk densities  $\rho_m(j)$  were true whereas the values  $Y_m$  were not. The corrected  $Y$  value ( $Y_C$ ) was calculated as follows:

$$Y_C = \frac{Y_m + (M_R - M(Y_m))}{\rho_m(Y_m)} \quad (6)$$

This correction allows, as previously, to obtain the same equivalent soil mass. The corresponding calculation of SOC stock ( $\text{SOC}_2$ , in  $\text{t ha}^{-1}$ ) is:

$$\text{SOC}_2(Y) = \sum_{j=1}^{Y_C} \rho_m(j) \cdot C(j) \quad (7)$$

Similar calculations were made for a greater depth (see Dimassi et al., 2013). The results presented below are the average of the two correction methods.

## 2.6. Statistical analysis

All analyses were performed using *R* statistical software. Tillage and time periods effects on crop yields were evaluated by ANOVA for each crop and crop management at the key dates (1982, 1994, 2002 and 2011) corresponding to the introduction of new crop managements. ANOVA was also performed on bulk densities measured in 2011 to evaluate the tillage and crop management effects in each layer.

Two linear mixed effect models were used to assess the effects of soil tillage, crop management and their interaction on SOC concentrations and stocks. The first one did not consider the auto-correlation that might exist between layers, while the second model accounted for a first order auto-correlation structure. The Akaike Information Criterion indicated that the second model was better and therefore retained in the subsequent analysis. We used the *nlme* package (Pinheiro and Bates, 2000) to fit the model and the *corAR1* function to describe the auto-correlation structure (Box et al., 1994). Significant differences between tillage treatments were found using *lsmeans* function. The assumptions of the linear mixed 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 applied to SOC concentrations and stocks in crop management CM1, for each soil layer and each key date (1970, 1982, 1994, 2002 and 2011) with tillage as fixed factor and plots/blocks as random

factor. It was also applied to all crop managements together considering tillage, residues, rotation and catch crops as fixed factors. Finally, temporal evolution of SOC stocks over time in each crop management was analyzed considering time as fixed factor and plots/blocks as random factor.

## 3. Results

### 3.1. Crop yields

The mean crop yields calculated over the four periods for each crop management and tillage treatment are presented at Table 2. The general trend for the main crop rotation (maize/wheat) was an increase in grain yields throughout time which was significant ( $p < 0.05$ ) between the first and the second periods for winter wheat and between the third and fourth time periods for maize. However, the average yields per time period were affected neither by tillage nor by crop management. Wheat yields rose from  $5.29$  to  $7.12 \text{ t ha}^{-1}$  (first to second period) and leveled off after 1995 at an average of  $7.44 \text{ t ha}^{-1}$ . The increase is due to the higher fertilization rate (from  $160$  to  $198 \text{ kg N ha}^{-1}$ ), the improvement in cultivar and crop protection. Maize yields also increased but later, after the second period (from  $5.77$  to  $6.75 \text{ t ha}^{-1}$ ) and the third period, reaching  $7.79 \text{ t ha}^{-1}$ , mainly due to the irrigation. During the second period (1983–1994), crop residues (wheat straw and maize stover) were removed from the CM6 management whereas they continued to be returned to the soil in the CM1 management. In spite of residues removal, neither wheat nor maize grain yields were affected during and after this period. Tillage treatments had no significant effect on grain yields in the new rotation introduced in 1998 (CM3 and CM4) as well as in crop managements CM2 and CM5 including catch crops since 2002. The absence of tillage effects on crop yields in all crop management systems suggests that C inputs derived from aerial crop residues were identical in all tillage treatments during the 41 years experiment.

### 3.2. Bulk densities

Bulk densities measured during the period 1974–1998, in 2002 and 2007 were all significantly affected by tillage. The mean bulk density in the old ploughed layer (0–Y) was always higher in the reduced tillage (ST and NT) than in the FIT treatment (results not shown). In 2011, it did not differ significantly between crop managements having the same crop rotation (maize–wheat rotation: CM1, CM2, CM5 and CM6; 4 years rotation: CM3 and CM4). The bulk density profile down to 40 cm depth for each crop rotation is shown in Appendix 3. Bulk densities increased from the top soil to 30 cm depth in all tillage treatments and decreased slightly below the old ploughed layer until 40 cm. They were significantly affected by tillage treatment in most layers: almost similar in the upper layer (0–5 cm), but significantly higher in NT and ST compared to FIT in layers 5–20 cm. The reverse trend was found below 25 cm depth with greater bulk densities in FIT than ST and NT. The difference between tillage treatments was smaller in the second rotation (wheat/sugarbeet/pea/barley) except in the deeper layers (>25 cm) which were more compacted in FIT than ST and NT.

### 3.3. SOC concentrations

The C concentrations of soil samples, measured regularly from 1970 until 2007 using the wet oxidation method, were re-analyzed later with the dry combustion method. The two methods gave very consistent results: C Anne (variable  $C_A$ ) was highly correlated to Dumas ( $C_D$ ): the regression equation was  $\hat{C}_D = 1.036C_A$  ( $r = 0.991$ ;  $n = 1730$ ). The subsequent SOC calculations were made with the mean of the two values ( $\hat{C}_D, C_D$ ).

#### 3.3.1. Initial and final concentrations in each crop management

In the whole study, we distinguished six layers in the soil profile: L1 = upper layer containing  $700 \text{ t soil ha}^{-1}$  corresponding to a mean depth of 0–5.2 cm; L2 containing  $800 \text{ t soil ha}^{-1}$  (5.2–10.8 cm); L3 containing  $800 \text{ t soil ha}^{-1}$  (10.8–16.4 cm); L4 containing  $1760 \text{ t soil ha}^{-1}$  (16.4–27.9 cm); L5 (27.9–31.4 cm) containing  $540 \text{ t soil ha}^{-1}$ ; L6 containing  $4000 \text{ t soil ha}^{-1}$  (31.4–58.4 cm). Layers L1–L4 correspond to the old ploughed layer. Layer L6 was sampled only in 2011. The mean values and confidence intervals of SOC concentration in each layer calculated on ESM basis for the CM1 management are given in Table 3. At the beginning of the experiment, all plots were under CM1. No significant differences in SOC concentrations were observed between tillage treatments in each layer indicating that the initial conditions were similar in all plots. These results were expected given the side by side plots location, the homogeneity in soil properties and the common crop management before 1970. SOC profile followed a uniform distribution over the ploughed layer (L1–L4) with a mean concentration of  $10.41 \text{ g kg}^{-1}$ , although the concentration was 9% lower in the layer L4 than in layers L1–L3. In layer L5, below the ploughed depth, SOC concentrations were about 50% lower than above with a mean value of  $5.23 \text{ g kg}^{-1}$ .

SOC distribution over the whole soil profile down to 60 cm measured in 2011 in each of the six crop managements is presented in Fig. 2. In the FIT treatment, the profile remained very homogeneous after 41 years. A typical stratified SOC distribution was observed for NT and ST whatever the crop management. Compared to

**Table 2**

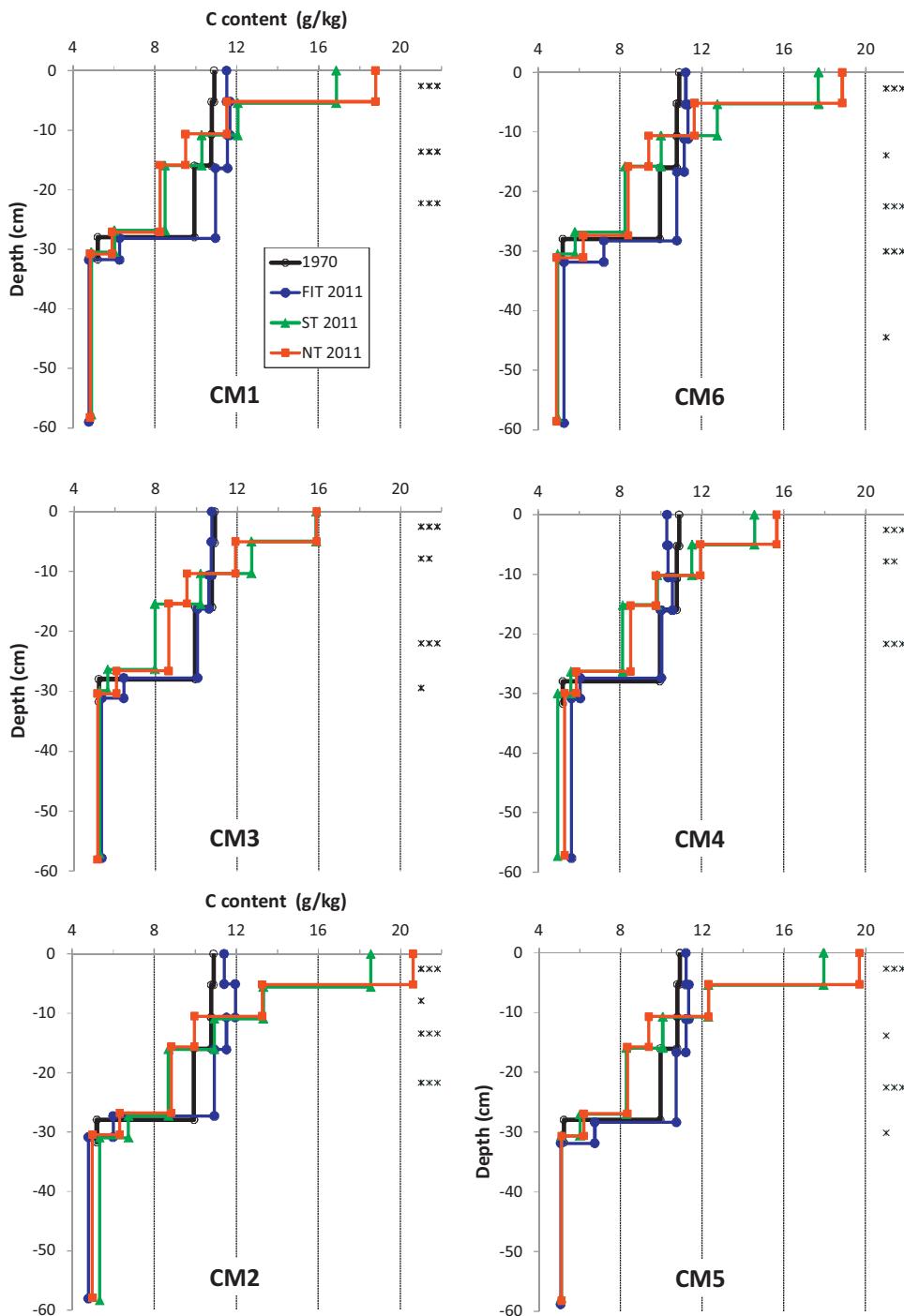
Mean crop yields ( $t \text{ DM ha}^{-1}$ ) versus tillage and crop management during four time periods. Lower case letters indicate significance ( $p < 0.05$ ) between tillage treatments for a given period; upper case letters indicate significance between periods for a given tillage treatment.

Crop management	Period	Crop	Tillage						Crop						Tillage						
			FIT			ST			NT			FIT			ST			NT			
CM1	1970–1982	Wheat	<b>5.34</b>	a	A	<b>5.29</b>	a	A	<b>5.40</b>	a	A	Maize	<b>5.65</b>	a	A	<b>5.59</b>	a	A	<b>5.29</b>	a	A
	1983–1994	Wheat	<b>7.18</b>	a	B	<b>7.19</b>	a	B	<b>7.15</b>	a	B	Maize	<b>5.75</b>	a	AB	<b>5.75</b>	a	AB	<b>5.84</b>	a	AB
	1995–2002	Wheat	<b>7.47</b>	a	B	<b>7.76</b>	a	B	<b>7.69</b>	a	B	Maize	<b>6.48</b>	a	B	<b>6.76</b>	a	B	<b>6.46</b>	a	B
	2003–2011	Wheat	<b>7.64</b>	a	B	<b>7.77</b>	a	B	<b>7.02</b>	a	B	Maize	<b>7.91</b>	a	C	<b>7.85</b>	a	C	<b>8.11</b>	a	C
CM2	1970–1982	Wheat	<b>5.34</b>	a	A	<b>5.29</b>	a	A	<b>5.40</b>	a	A	Maize	<b>5.65</b>	a	A	<b>5.59</b>	a	A	<b>5.29</b>	a	A
	1983–1994	Wheat	<b>7.18</b>	a	B	<b>7.19</b>	a	B	<b>7.15</b>	a	B	Maize	<b>5.75</b>	a	A	<b>5.75</b>	a	A	<b>5.84</b>	a	A
	1995–2002	Wheat	<b>7.47</b>	a	BC	<b>7.76</b>	a	BC	<b>7.69</b>	a	BC	Maize	<b>6.48</b>	a	AB	<b>6.76</b>	a	AB	<b>6.46</b>	a	AB
	2003–2011	Wheat	<b>7.68</b>	ab	B	<b>7.84</b>	a	B	<b>6.94</b>	b	B	Maize	<b>7.97</b>	a	B	<b>8.00</b>	a	B	<b>8.13</b>	a	B
CM3	1970–1982	Wheat	<b>5.01</b>	a	A	<b>5.14</b>	a	A	<b>5.35</b>	a	A	Maize	<b>5.50</b>	a	A	<b>5.42</b>	a	A	<b>5.10</b>	a	A
	1983–1994	Wheat	<b>7.11</b>	a	B	<b>6.98</b>	a	B	<b>7.01</b>	a	B	Maize	<b>5.81</b>	a	A	<b>5.71</b>	a	A	<b>5.77</b>	a	A
	1995–2002	Wheat	<b>7.12</b>	a	B	<b>6.96</b>	a	B	<b>7.19</b>	a	B	Pea	<b>4.24</b>	a	A	<b>4.52</b>	a	A	<b>4.37</b>	a	A
	1995–2002	Barley	<b>6.67</b>	a	A	<b>6.22</b>	a	A	<b>6.35</b>	a	A	Sugarbeet	<b>14.7</b>	a	A	<b>15.3</b>	a	A	<b>15.2</b>	a	A
	2003–2011	Wheat	<b>7.11</b>	a	B	<b>7.37</b>	a	B	<b>7.25</b>	a	B	Pea	<b>3.52</b>	a	B	<b>3.19</b>	a	B	<b>3.31</b>	a	B
	2003–2011	Barley	<b>7.33</b>	a	A	<b>6.52</b>	a	A	<b>6.76</b>	a	A	Sugarbeet	<b>16.8</b>	a	B	<b>14.8</b>	a	B	<b>14.0</b>	a	B
CM4	1970–1982	Wheat	<b>5.29</b>	a	A	<b>5.29</b>	a	A	<b>5.30</b>	a	A	Maize	<b>5.47</b>	a	A	<b>5.38</b>	a	A	<b>5.03</b>	a	A
	1983–1994	Wheat	<b>7.05</b>	a	B	<b>7.04</b>	a	B	<b>6.89</b>	a	B	Maize	<b>5.67</b>	a	A	<b>5.72</b>	a	A	<b>5.59</b>	a	A
	1995–2002	Wheat	<b>6.68</b>	a	B	<b>6.81</b>	a	B	<b>7.04</b>	a	B	Pea	<b>4.79</b>	a	A	<b>4.07</b>	a	A	<b>4.22</b>	a	A
	1995–2002	Barley	<b>6.11</b>	a	A	<b>6.15</b>	a	A	<b>6.06</b>	a	A	Sugarbeet	<b>15.6</b>	a	A	<b>18.4</b>	a	A	<b>18.5</b>	a	A
	2003–2011	Wheat	<b>7.89</b>	a	B	<b>7.10</b>	a	B	<b>7.07</b>	a	B	Pea	<b>3.86</b>	a	B	<b>3.25</b>	a	B	<b>3.15</b>	a	B
	2003–2011	Barley	<b>6.21</b>	a	A	<b>6.62</b>	a	A	<b>6.39</b>	a	A	Sugarbeet	<b>15.0</b>	a	B	<b>17.6</b>	a	B	<b>18.2</b>	a	B
CM5	1970–1982	Wheat	<b>5.11</b>	a	A	<b>5.34</b>	a	A	<b>5.44</b>	a	A	Maize	<b>5.70</b>	a	A	<b>5.47</b>	a	A	<b>5.35</b>	a	A
	1983–1994	Wheat	<b>7.15</b>	a	B	<b>7.14</b>	a	B	<b>7.20</b>	a	B	Maize	<b>5.66</b>	a	A	<b>5.74</b>	a	A	<b>6.03</b>	a	A
	1995–2002	Wheat	<b>7.86</b>	a	BC	<b>8.14</b>	a	BC	<b>8.15</b>	a	BC	Maize	<b>7.54</b>	a	AB	<b>7.24</b>	a	AB	<b>7.25</b>	a	AB
	2003–2011	Wheat	<b>7.44</b>	a	B	<b>7.51</b>	a	B	<b>7.32</b>	a	B	Maize	<b>7.57</b>	a	B	<b>7.18</b>	a	B	<b>7.70</b>	a	B
CM6	1970–1982	Wheat	<b>5.11</b>	a	A	<b>5.34</b>	a	A	<b>5.44</b>	a	A	Maize	<b>5.70</b>	a	A	<b>5.47</b>	a	A	<b>5.35</b>	a	A
	1983–1994	Wheat	<b>7.15</b>	a	B	<b>7.14</b>	a	B	<b>7.20</b>	a	B	Maize	<b>5.66</b>	a	AB	<b>5.74</b>	a	AB	<b>6.03</b>	a	AB
	1995–2002	Wheat	<b>7.63</b>	a	B	<b>7.63</b>	a	B	<b>7.75</b>	a	B	Maize	<b>6.43</b>	a	B	<b>6.66</b>	a	B	<b>6.44</b>	a	B
	2003–2011	Wheat	<b>7.53</b>	a	B	<b>7.39</b>	a	B	<b>7.25</b>	a	B	Maize	<b>7.56</b>	a	C	<b>7.37</b>	a	C	<b>8.10</b>	a	C
All	1970–1982	Wheat	<b>5.20</b>	A		<b>5.28</b>	A		<b>5.39</b>	A		Maize	<b>5.61</b>	A		<b>5.49</b>	A		<b>5.24</b>	A	
	1983–1994	Wheat	<b>7.14</b>	B		<b>7.11</b>	B		<b>7.10</b>	B		Maize	<b>5.72</b>	A		<b>5.73</b>	A		<b>5.85</b>	A	
	1995–2002	Wheat	<b>7.37</b>	C		<b>7.51</b>	C		<b>7.58</b>	C		Maize	<b>6.73</b>	B		<b>6.85</b>	B		<b>6.65</b>	B	
	2003–2011	Wheat	<b>7.55</b>	C		<b>7.50</b>	C		<b>7.14</b>	B		Maize	<b>7.75</b>	C		<b>7.60</b>	C		<b>8.01</b>	C	

**Table 3**

SOC concentrations versus depth and time at equivalent soil mass in the crop management CM1. Confidence intervals ( $p < 0.05$ ) are given in brackets. Lower case letters indicate significance between tillage treatments for a given date.

Year	Layer	Soil mass ( $\text{t ha}^{-1}$ )	FIT			ST			NT		
			Depth (cm)	SOC concentration ( $\text{g kg}^{-1}$ )		Depth (cm)	SOC concentration ( $\text{g kg}^{-1}$ )		Depth (cm)	SOC concentration ( $\text{g kg}^{-1}$ )	
1970	L1	700	0.0–5.2	<b>10.89</b> (0.46)	a	0.0–5.2	<b>10.96</b> (0.25)	a	0.0–5.2	<b>11.04</b> (0.29)	a
	L2	800	5.2–10.7	<b>10.77</b> (0.56)	a	5.2–10.8	<b>10.66</b> (0.22)	a	5.2–10.6	<b>10.87</b> (0.25)	a
	L3	800	10.7–16.0	<b>10.76</b> (0.43)	a	10.8–16.1	<b>10.66</b> (0.19)	a	10.6–15.9	<b>10.79</b> (0.24)	a
	L4	1760	16.0–28.0	<b>9.94</b> (0.39)	a	16.1–28.1	<b>9.79</b> (0.26)	a	15.9–27.9	<b>9.92</b> (0.27)	a
	L5	540	28.0–31.7	<b>5.20</b> (0.42)	a	28.1–31.8	<b>5.17</b> (0.37)	a	27.9–31.7	<b>5.31</b> (0.48)	a
1982	L1	700	0.0–5.1	<b>10.59</b> (0.60)	a	0.0–5.0	<b>13.96</b> (0.49)	b	0.0–5.1	<b>15.70</b> (0.47)	c
	L2	800	5.1–10.7	<b>10.33</b> (0.37)	a	5.0–10.2	<b>13.14</b> (0.27)	b	5.1–10.1	<b>10.44</b> (0.23)	a
	L3	800	10.7–16.4	<b>10.44</b> (0.36)	ab	10.2–15.1	<b>10.37</b> (0.38)	a	10.1–15.0	<b>9.84</b> (0.25)	b
	L4	1760	16.4–28.5	<b>10.20</b> (0.31)	a	15.1–26.2	<b>9.22</b> (0.26)	b	15.0–25.7	<b>9.08</b> (0.33)	b
	L5	540	28.5–32.2	<b>5.79</b> (0.39)	a	26.2–30.0	<b>6.36</b> (0.18)	a	25.7–27.9	<b>6.09</b> (0.29)	a
1994	L1	700	0.0–5.1	<b>11.30</b> (0.45)	a	0.0–5.1	<b>15.82</b> (0.38)	b	0.0–5.3	<b>21.30</b> (0.88)	c
	L2	800	5.1–10.9	<b>11.30</b> (0.45)	a	5.1–10.4	<b>14.53</b> (0.32)	b	5.3–10.4	<b>11.09</b> (0.41)	a
	L3	800	10.9–16.6	<b>11.30</b> (0.45)	a	10.4–15.5	<b>11.22</b> (0.38)	a	10.4–15.5	<b>9.71</b> (0.35)	b
	L4	1760	16.6–28.8	<b>10.43</b> (0.47)	a	15.5–26.8	<b>9.78</b> (0.28)	b	15.5–26.7	<b>9.06</b> (0.29)	c
	L5	540	28.8–32.5	<b>5.94</b> (0.37)	a	26.8–30.6	<b>6.28</b> (0.49)	a	26.7–30.5	<b>6.32</b> (0.24)	a
2002	L1	700	0.0–5.4	<b>12.10</b> (0.93)	a	0.0–5.6	<b>16.02</b> (1.50)	b	0.0–5.8	<b>17.68</b> (0.90)	b
	L2	800	5.4–10.8	<b>11.84</b> (0.27)	a	5.6–10.9	<b>12.07</b> (1.39)	a	5.8–11.3	<b>9.83</b> (0.40)	b
	L3	800	10.8–16.0	<b>11.40</b> (0.29)	a	10.9–16.0	<b>10.14</b> (1.08)	a	11.3–16.4	<b>8.61</b> (0.34)	b
	L4	1760	16.0–27.1	<b>10.42</b> (0.37)	a	16.0–27.1	<b>8.39</b> (0.52)	b	16.4–27.7	<b>8.10</b> (0.31)	b
	L5	540	27.1–30.7	<b>6.02</b> (0.08)	a	27.1–30.7	<b>5.84</b> (0.18)	a	27.7–31.5	<b>5.63</b> (0.20)	a
2011	L1	700	0.0–5.2	<b>11.50</b> (0.90)	a	0.0–5.5	<b>16.86</b> (2.00)	b	0.0–5.2	<b>18.78</b> (3.07)	b
	L2	800	5.2–10.9	<b>11.67</b> (1.39)	a	5.5–10.9	<b>12.05</b> (0.98)	a	5.2–10.7	<b>11.51</b> (0.78)	a
	L3	800	10.9–16.4	<b>11.55</b> (0.90)	a	10.9–15.9	<b>10.28</b> (0.84)	b	10.7–15.8	<b>9.49</b> (0.24)	b
	L4	1760	16.4–28.1	<b>10.96</b> (0.09)	a	15.9–26.9	<b>8.49</b> (0.65)	b	15.8–27.1	<b>8.25</b> (0.33)	b
	L5	540	28.1–31.8	<b>6.27</b> (0.77)	a	26.9–30.5	<b>6.02</b> (0.43)	a	27.1–30.8	<b>5.91</b> (0.33)	a
	L6	4000	31.8–57.2	<b>4.77</b> (0.15)	a	30.5–55.9	<b>4.89</b> (0.36)	a	30.8–56.4	<b>4.83</b> (0.29)	a



**Fig. 2.** Profile of SOC concentration in each tillage treatment and for each crop management (CM1–CM6) measured in 1970 and 2011. The asterisks indicate significant differences between tillage treatments in each of the six soil layers.

FIT, NT and ST treatments showed significant higher SOC concentrations in layer L1 in all CM ( $p < 0.001$ ), as well as in layer L2 but significant in three CM out of six. Conversely, concentrations were smaller in layer L3, in a significant way in four CM and always lower ( $p < 0.001$ ) in layer L4. SOC concentration in layer L5 was equal or smaller in CM3, CM5 and CM6. Finally SOC concentrations in the deeper layer L6 were small and very homogeneous (mean value = 5.14, 5.08 and 5.04 g kg<sup>-1</sup> in FIT, ST and NT, respectively), so that no significant differences were recorded except for CM6.

### 3.3.2. Temporal variation of SOC concentration

Table 3 shows the SOC concentrations at the five key dates in crop management CM1. SOC concentration showed a progressive increase over time which appears clearly in FIT in all layers (L1–L5). In the reduced tillage treatments (ST and NT), concentration increased markedly in the upper layers (L1 and L2 for ST and L1 for NT)

but decreased in layers L3 and L4. Statistical comparisons between tillage treatments at a given date confirmed this trend, indicating that SOC concentrations in reduced tillage were always significantly greater than those in FIT in layer L1 and smaller in layer L4, from 1982 until 2011. Significant differences appeared between ST and NT in 1982, 1994 and 2002: ST had smaller concentrations than NT in layer L1 and greater in layers L2 and L3. The differences disappeared in 2011, probably because the tillage depth of ST was reduced after 2002.

The statistical analysis of cropping practices (tillage, residues, rotation and catch crops) is given in Appendix 4. Tillage significantly affected SOC concentrations in all layers except layer L2 and L6 in 2011. Residues removal during 12 years significantly reduced SOC concentration in all layers (L1–L4) in 1994, 2002 and 2011 except for layers L2 and L4. There was almost no effect of rotation in 2002 and 2011, no effect of catch crops in 2011, and no interaction between tillage and the three other cropping practices in all layers above the old ploughed depth (L1–L4).

**Table 4**

Cumulative SOC stocks ( $t\text{Cha}^{-1}$ ) on ESM basis in 1970 and 2011 (mean of methods 1 and 2). Values in brackets are the confidence intervals ( $p < 0.05$ ). Letters indicate significant differences between tillage treatments. Bold values correspond to the old ploughed layer ( $4060\text{ t soil ha}^{-1}$ ).

Crop management	FIT				ST				NT			
	Year	Soil mass ( $\text{t ha}^{-1}$ )	Depth (cm)	SOC ( $\text{t ha}^{-1}$ )	Depth (cm)	SOC ( $\text{t ha}^{-1}$ )	Depth (cm)	SOC ( $\text{t ha}^{-1}$ )	Depth (cm)	SOC ( $\text{t ha}^{-1}$ )	Depth (cm)	SOC ( $\text{t ha}^{-1}$ )
All	1970	700	5.2	7.62 (0.31)	a	5.2	7.66 (0.19)	a	5.2	7.72 (0.20)	a	
		1500	10.7	16.25 (0.75)	a	10.8	16.22 (0.33)	a	10.6	16.44 (0.38)	a	
		2300	16.0	24.84 (1.04)	a	16.1	24.72 (0.47)	a	15.9	25.04 (0.54)	a	
		<b>4060</b>	<b>28.0</b>	<b>42.32</b> <b>(1.42)</b>	<b>a</b>	<b>28.1</b>	<b>41.96</b> <b>(0.75)</b>	<b>a</b>	<b>27.9</b>	<b>42.52</b> <b>(0.88)</b>	<b>a</b>	
		4600	31.7	45.15 (1.54)	a	31.8	44.76 (0.82)	a	31.7	45.39 (1.00)	a	
CM1	2011	700	5.2	8.07 (0.64)	a	5.5	11.81 (1.38)	b	5.2	13.17 (2.13)	b	
		1500	10.9	17.41 (1.69)	a	10.9	21.43 (1.96)	b	10.7	22.36 (2.50)	b	
		2300	16.4	26.63 (2.45)	a	15.9	29.67 (2.50)	a	15.8	29.96 (2.63)	a	
		<b>4060</b>	<b>28.1</b>	<b>45.91</b> <b>(2.67)</b>	<b>a</b>	<b>26.9</b>	<b>44.59</b> <b>(3.37)</b>	<b>a</b>	<b>27.1</b>	<b>44.48</b> <b>(3.05)</b>	<b>a</b>	
		4600	31.8	49.32 (2.79)	a	30.5	47.86 (3.28)	a	30.8	47.66 (3.04)	a	
		8600	57.2	68.40 (2.53)	a	55.9	67.41 (3.18)	a	56.4	66.99 (3.90)	a	
CM2	2011	700	5.1	8.01 (0.87)	a	5.6	12.99 (0.77)	b	5.2	14.41 (1.43)	c	
		1500	10.7	17.56 (1.88)	a	10.9	23.64 (0.76)	b	10.5	25.02 (1.62)	b	
		2300	16.1	26.78 (2.54)	a	16.1	32.37 (0.91)	b	15.6	33.00 (1.88)	b	
		<b>4060</b>	<b>27.3</b>	<b>45.96</b> <b>(2.21)</b>	<b>a</b>	<b>27.3</b>	<b>47.65</b> <b>(1.17)</b>	<b>ab</b>	<b>26.8</b>	<b>48.53</b> <b>(2.51)</b>	<b>b</b>	
		4600	30.9	49.19 (1.99)	a	31.0	51.31 (1.29)	ab	30.4	51.95 (2.55)	b	
		8600	56.3	68.38 (2.55)	a	56.5	72.71 (2.60)	b	56.1	71.91 (3.68)	ab	
CM3	2011	700	5.1	7.50 (0.12)	a	5.0	11.03 (1.13)	b	5.0	11.14 (1.24)	b	
		1500	10.6	16.09 (0.49)	a	10.4	21.26 (0.96)	b	10.3	20.66 (1.02)	b	
		2300	16.3	24.59 (0.56)	a	15.5	29.41 (1.18)	b	15.4	28.26 (0.99)	b	
		<b>4060</b>	<b>27.8</b>	<b>42.29</b> <b>(0.93)</b>	<b>a</b>	<b>26.3</b>	<b>43.42</b> <b>(1.57)</b>	<b>a</b>	<b>26.6</b>	<b>43.46</b> <b>(0.89)</b>	<b>a</b>	
		4600	31.2	45.75 (0.77)	a	29.9	46.44 (1.55)	a	30.4	46.76 (0.90)	a	
		8600	56.2	67.15 (0.94)	a	55.3	68.24 (0.64)	a	56.2	67.33 (1.62)	a	
CM4	2011	700	5.2	7.20 (0.56)	a	5.0	10.17 (0.82)	b	5.0	11.02 (1.35)	b	
		1500	10.5	15.42 (1.45)	a	10.2	19.39 (1.21)	b	10.2	20.48 (1.64)	b	
		2300	16.0	23.95 (1.63)	a	15.2	27.25 (1.39)	b	15.2	28.30 (2.10)	b	
		<b>4060</b>	<b>27.4</b>	<b>41.56</b> <b>(2.45)</b>	<b>a</b>	<b>26.3</b>	<b>41.57</b> <b>(1.78)</b>	<b>ab</b>	<b>26.3</b>	<b>43.31</b> <b>(2.81)</b>	<b>b</b>	
		4600	30.9	44.86 (2.27)	a	30.0	44.57 (1.89)	ab	29.9	46.45 (2.92)	b	
		8600	56.0	66.15 (2.20)	a	55.5	63.48 (2.08)	a	55.4	66.83 (5.14)	a	
CM5	2011	700	5.3	7.83 (0.62)	a	5.4	12.53 (0.74)	b	5.3	13.82 (2.56)	b	
		1500	11.1	16.90 (1.36)	a	10.7	22.35 (0.79)	b	10.7	23.64 (3.43)	b	
		2300	16.7	25.81 (2.01)	a	15.9	30.41 (1.08)	a	15.7	31.12 (4.17)	a	
		<b>4060</b>	<b>28.4</b>	<b>44.69</b> <b>(2.19)</b>	<b>a</b>	<b>27.0</b>	<b>44.96</b> <b>(1.74)</b>	<b>a</b>	<b>26.9</b>	<b>45.76</b> <b>(5.34)</b>	<b>a</b>	
		4600	31.9	48.32 (2.41)	a	30.6	48.20 (1.95)	a	30.6	49.08 (5.44)	a	
		8600	57.1	68.54 (3.02)	a	56.0	68.52 (2.79)	a	56.4	69.48 (6.46)	a	
CM6	2011	700	5.4	7.84 (0.84)	a	5.3	12.33 (0.84)	b	5.2	13.22 (1.45)	b	
		1500	11.2	16.91 (1.55)	a	10.6	22.55 (0.91)	b	10.6	22.54 (2.20)	b	
		2300	16.7	25.80 (1.86)	a	15.8	30.56 (1.09)	b	15.8	30.03 (2.76)	b	
		<b>4060</b>	<b>28.3</b>	<b>44.76</b> <b>(0.26)</b>	<b>a</b>	<b>26.8</b>	<b>45.07</b> <b>(1.40)</b>	<b>a</b>	<b>27.4</b>	<b>44.81</b> <b>(3.43)</b>	<b>a</b>	
		4600	31.8	48.67 (0.46)	a	30.5	48.21 (1.51)	a	31.1	48.16 (3.68)	a	
		8600	57.1	69.72 (1.30)	a	56.0	68.00 (1.56)	a	56.7	67.75 (4.64)	a	
All	2011	700	5.2	7.74 (0.33)	a	5.3	11.81 (1.05)	b	5.1	12.80 (1.40)	b	
		1500	10.8	16.72 (0.82)	a	10.6	21.77 (1.45)	b	10.5	22.45 (1.74)	b	
		2300	16.4	25.59 (1.12)	a	15.7	29.95 (1.68)	b	15.6	30.11 (1.80)	b	
		<b>4060</b>	<b>27.9</b>	<b>44.20</b> <b>(1.85)</b>	<b>a</b>	<b>26.8</b>	<b>44.54</b> <b>(2.01)</b>	<b>a</b>	<b>26.9</b>	<b>45.06</b> <b>(1.93)</b>	<b>a</b>	
		4600	31.4	47.68 (1.90)	a	30.4	47.77 (2.23)	a	30.5	48.34 (2.01)	a	
		8600	56.6	68.06 (1.24)	a	55.9	68.06 (2.94)	a	56.2	68.38 (1.97)	a	

### 3.4. SOC stocks

#### 3.4.1. Comparison between calculation methods

As indicated previously, the SOC stock depends on the reference soil mass in the old ploughed layer and the correction method used for calculating ESM. We conducted a sensitivity analysis of SOC to both parameters (Appendix 5). It showed that the SOC differences due to variation in reference soil mass remained almost constant whatever the tillage treatment. The effect of correction method depends on tillage treatment: M1 and M2 gave very close results in FIT and small differences in ST and NT which were not significant. These results suggest that in spite of experimental errors in measuring Y depth and bulk density, reliable conclusions can be made on the variations of SOC stocks versus time and tillage treatments, confirming previous results (Dimassi et al., 2013).

#### 3.4.2. Initial and final SOC stocks

The cumulative SOC stocks calculated in 1970 and 2011 for each layer and each crop management and tillage treatment are given in Table 4. At the beginning of the experiment no statistical difference appeared between tillage treatments whatever the soil layer. SOC stocks over the old ploughed layer (L1–L4) were 42.3, 42.0 and 42.5 t ha<sup>-1</sup> for FIT, ST and NT, respectively. In 2011, reduced tillage resulted in higher stocks in layer L1 + L2 and lower stocks in layer L3 + L4. No significant differences were found between tillage treatments over the old ploughed layer, except for crop managements CM2 and CM4 where NT was slightly greater than FIT. There was no significant difference, neither between FIT and ST nor between ST and NT, whatever the crop management. The mean SOC stocks of all crop managements were 44.2, 44.5 and 45.1 t ha<sup>-1</sup> for FIT, ST and NT, respectively. If we consider all layers (L1–L6, ca. 0–58 cm), SOC stocks were absolutely similar: 68.1, 68.1 and 68.4 t ha<sup>-1</sup>, respectively.

#### 3.4.3. Temporal variation

The effect of cropping practices on SOC stocks in the old ploughed layer was evaluated statistically at the 5 key dates (Appendix 6). Tillage significantly affected SOC stocks in 1982 and 1994 but not later. Residues removal effect was quite significant in 1994, but not later. Rotation and catch crops had no significant effect on SOC stocks in 2002 and 2011. There was no interaction between tillage and residues, even in 1994. Fig. 3 illustrates the temporal changes in SOC stocks during the 41 years for each crop management and tillage treatment. Since crop managements were established progressively throughout time, the first periods were common to several crop managements so that SOC stocks were similar and are represented without confidence intervals. The general trend in crop managements CM1 and CM2 is an increase in SOC stocks from 1970 to 1998, followed by a stabilization or a decrease. In CM6 and CM5, with a similar crop ration (maize/wheat) but an export of crop residues during 12 years, SOC stocks remained rather constant from 1982 to 1998 and either stable or decreasing after 1998. The 4 years rotation, established in 1998 (CM3 and CM4), lead to a decrease in SOC stocks from 1998 to 2011. The second trend is a greater SOC content in reduced tillage treatments until 1998 and then a more or less similar content than in FIT treatment.

#### 3.4.4. Rate of change in SOC content

The rate of change in SOC stocks was calculated during the main four periods, as the slope of the linear regression of SOC versus time. Table 5 summarizes the rates in three pooled layers: L1 + L2 (ca. 0–10 cm), L3 + L4 (ca. 10–28 cm) and L1–L4 (ca. 0–28 cm). In the first period 1970–1982, common to all crop managements, SOC stock increased significantly in ST in the layers 0–10 and 0–28 cm (rate = +0.20 t Ch<sup>-1</sup> yr<sup>-1</sup>) and decreased significantly in NT in the layer 10–28 cm. In the second period 1982–1994, SOC increased significantly in ST and NT in CM1 in layers 0–10 and 0–28 cm (rate = 0.30 and 0.35 t Ch<sup>-1</sup> yr<sup>-1</sup>, resp.), and remained stable in the layer 0–28 cm in CM6 where crop residues were removed. From 1994 to 2002, SOC decreased significantly in ST and NT in all layers (rate = -0.64 and -0.76 t Ch<sup>-1</sup> yr<sup>-1</sup>, resp.), but not in the FIT treatment. A similar decrease also occurred in CM6, but it was smaller. During the last period (2002–2011), few changes were significant, except in CM2 and CM5. In these two crop managements, the introduction of catch crops resulted in a frequent significant increase in SOC stocks particularly for reduced tillage treatments. Finally, if we consider CM1 over the whole period (1970–2011), there was a SOC increase although not significant in the surface layer (0–10 cm) in all tillage treatments, a significant decrease in the deeper layer (10–28 cm) in the reduced tillage treatments and almost no change in the old ploughed layer whatever the tillage. The effect of reduced tillage was analyzed by difference with FIT. Since no interaction was found between tillage and the other cropping practices, we could average them. Fig. 4 shows the differences ST–FIT and NT–FIT versus time. It emphasizes the rapid C sequestration due to reduced tillage during the first years followed by a plateau and then a drop after 1998 which cancelled the benefit of reduced tillage obtained after 28 years.

#### 3.4.5. Effect of climatic factors

The important drop in SOC stocks between 1998 and 2002 in the reduced tillage treatments was surprising. No change in methodology could explain this loss. We examined climatic factors susceptible to influence the C mineralization rate and therefore the SOC stocks by comparing the rates of change in SOC stocks ( $\Delta$ SOC/ $\Delta$ t) during the 4 years sequences preceding each date of measurement to five

**Table 5**  
Rates of change in SOC content (t Ch<sup>-1</sup> yr<sup>-1</sup>) during each time period and crop management: mean value and statistical significance. Asterisks indicate probability of a rate different from 0.

Period	Years	Crop management	Layer 0–10 cm <sup>a</sup>						Layer 10–28 cm <sup>b</sup>						Layer 0–28 cm <sup>c</sup>						
			ST			NT			ST			NT			ST			NT			
			FIT	0.34	0.23	0.01	0.14	*	-0.14	0.01	0.14	*	-0.21	***	-0.04	0.20	**	0.02	0.35	***	
1	1970	1982	CM1	-0.05	0.34	0.23	0.01	0.14	*	-0.14	0.01	0.14	*	-0.21	***	-0.04	0.20	**	0.02	0.35	***
	1982	1994	CM1	0.10	0.16	0.37	0.07	0.14	*	-0.11	0.01	0.11	*	-0.11	***	-0.09	0.30	**	0.05	0.05	***
			CM6	-0.02	-0.01	0.16	-0.06	-0.06		-0.40	***	-0.32	***	-0.13	***	-0.64	**	-0.76	***		***
			CM1	0.13	-0.23	0.44	0.00	-0.40	***	-0.09	0.04	0.04	*	-0.33	**	-0.33	-0.18				***
			CM6	0.06	-0.02	-0.10	-0.03	-0.30		-0.09	0.04	0.04	*	-0.33	**	-0.33					***
			CM1	-0.06	0.07	0.23	0.11	0.02	0.10	0.02	0.10	0.02	0.10	0.05	0.05	0.10	0.10	0.33	***	0.32	***
2	1994	2002	CM1	0.13	-0.23	0.44	0.00	-0.40	***	-0.09	0.04	0.04	*	-0.33	**	-0.33					***
			CM6	0.06	-0.02	-0.10	-0.03	-0.30		-0.09	0.04	0.04	*	-0.33	**	-0.33					***
			CM1	-0.06	0.07	0.23	0.11	0.02	0.10	0.02	0.10	0.02	0.10	0.05	0.05	0.10	0.10	0.33	***	0.32	***
			CM6	0.06	**	0.33	0.27	0.20	*	0.11	0.05	0.05	*	0.27	**	0.44	0.44	0.44	0.44	***	
			CM3	-0.05	-0.12	-0.24	-0.03	-0.10	0.03	-0.10	0.03	0.03	0.03	0.08	0.08	-0.08	-0.22	-0.21	-0.21	***	
			CM4	-0.09	-0.04	-0.13	0.03	0.11	0.11	0.12	*	0.12	*	0.26	***	-0.06	-0.02	-0.05	-0.05	***	
3	2002	2011	CM1	-0.06	*	0.31	0.53	***	0.11	0.13	0.13	0.13	0.05	0.05	0.06	0.06	0.43	*	0.79	***	
			CM6	0.06	*	0.30	0.39	0.21	*	0.13	0.05	0.05	*	-0.07	***	-0.12	0.44	0.44	0.43	***	
			CM1	0.06	*	0.13	0.13	0.05	*	0.05	*	0.05	*	-0.07	***	0.10	0.05	0.01	0.01	***	
			CM6	0.06	*	0.13	0.13	0.05	*	0.05	*	0.05	*	-0.07	***	0.10	0.05	0.01	0.01	***	
			CM3	-0.05	*	0.11	0.11	0.05	*	0.05	*	0.05	*	-0.07	***	0.10	0.05	0.01	0.01	***	
			CM4	-0.09	*	0.11	0.11	0.05	*	0.05	*	0.05	*	-0.07	***	0.10	0.05	0.01	0.01	***	
4	2002	2011	CM1	-0.06	*	0.31	0.53	***	0.11	0.13	0.13	0.13	0.05	0.05	0.06	0.06	0.43	*	0.79	***	
			CM6	0.06	*	0.30	0.39	0.21	*	0.13	0.05	0.05	*	-0.07	***	0.10	0.05	0.01	0.01	***	
			CM1	0.06	*	0.13	0.13	0.05	*	0.05	*	0.05	*	-0.07	***	0.10	0.05	0.01	0.01	***	
			CM6	0.06	*	0.13	0.13	0.05	*	0.05	*	0.05	*	-0.07	***	0.10	0.05	0.01	0.01	***	
			CM3	-0.05	*	0.11	0.11	0.05	*	0.05	*	0.05	*	-0.07	***	0.10	0.05	0.01	0.01	***	
			CM4	-0.09	*	0.11	0.11	0.05	*	0.05	*	0.05	*	-0.07	***	0.10	0.05	0.01	0.01	***	
All	1970	2011	CM1	0.06	*	0.13	0.13	0.05	*	0.05	*	0.05	*	-0.07	***	-0.12	0.44	0.44	0.43	***	

<sup>a</sup> Approximate depth corresponding to a constant soil mass of 1500 t ha<sup>-1</sup>.

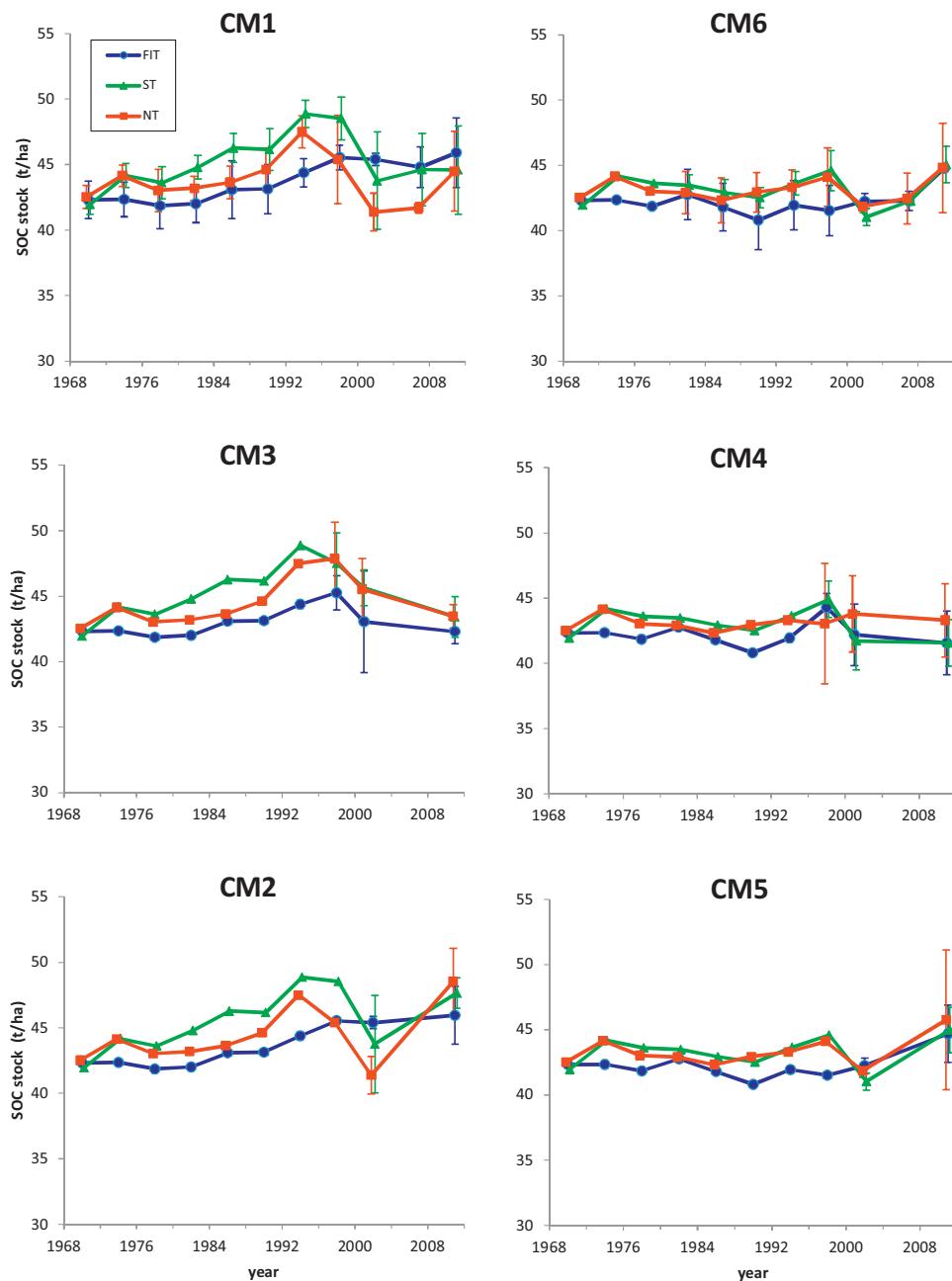
<sup>b</sup> Approximate depth corresponding to a constant soil mass of 2560 t ha<sup>-1</sup>.

<sup>c</sup> Approximate depth corresponding to a constant soil mass of 4060 t ha<sup>-1</sup>.

\* p < 0.05.

\*\* p < 0.01.

\*\*\* p < 0.001.



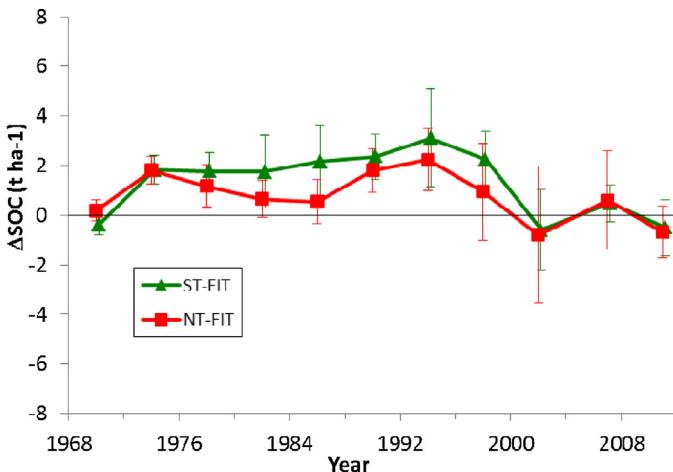
**Fig. 3.** Evolution of SOC stocks over time in each tillage treatment and crop management (CM1–CM6). Vertical bars indicate confidence intervals ( $p < 0.05$ ). The reference treatment is CM1. In treatments CM2–CM6, the SOC stocks measured before the initiation of the changes in crop management are represented without the confidence intervals.

indicators measured during the same periods: the mean air temperature ( $T$ ), precipitation ( $P$ ), precipitation + irrigation ( $P+I$ ), water balance ( $PI - PET$ ) and aridity index ( $(P+I)/PET$ ). During the 10 sequences of 4 years, the mean temperature varied from 10.0 to 11.8 °C, precipitation + irrigation from 518 to 798 mm yr $^{-1}$  and the water balance from -232 to +126 mm yr $^{-1}$ . The coefficients of correlation between these variables are given in Appendix 7. All significant coefficients were negative, indicating that SOC decreased when temperature or moisture availability increased and vice versa. A significant but weak correlation was found between  $\Delta$ SOC and temperature ( $r = -0.28$ ;  $n = 68$ ;  $p < 0.05$ ). The four indicators of water availability explained a much greater proportion of  $\Delta$ SOC variance, particularly for the reduced tillage treatments. They gave rather similar results, showing that precipitation was the main factor explaining the  $\Delta$ SOC changes, and that the (moderate) irrigation only increased the water availability effect. The highest correlation was found in the upper layer of NT treatment ( $r = -0.80$ ;  $p < 0.001$ ; Fig. 5). It is mainly due to the high water balance observed in the period 1998–2002 with very wet years. These results suggest that the water balance may strongly affect SOC stocks, particularly in reduced tillage systems.

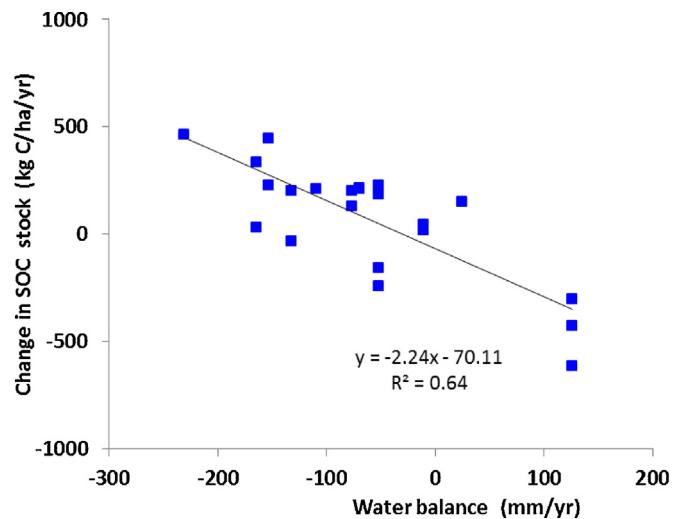
## 4. Discussion

### 4.1. Distribution of SOC concentration in the soil profile

Continuous no-till and shallow tillage led on the long-term (41 years) to a pronounced SOC stratification throughout the soil profile as opposed to FIT which maintained a rather uniform distribution over the soil profile down to the current ploughing depth. These results agree with two recent meta-analyses which examined the SOC distribution throughout the profile. Luo et al., 2010a, compiling 69 paired experiments with a mean duration of 13 years, found high significant increase in the top 10 cm of soil under NT, a decline in the 20–40 cm layer and no significant difference below 40 cm depth. Similar results were reported in the meta-analysis



**Fig. 4.** Evolution of the differences in SOC stocks between reduced tillage (ST and NT) and full inversion tillage (FIT) versus time: mean of all treatments (CM1–CM6). Vertical bars represent the confidence intervals ( $p < 0.05$ ).

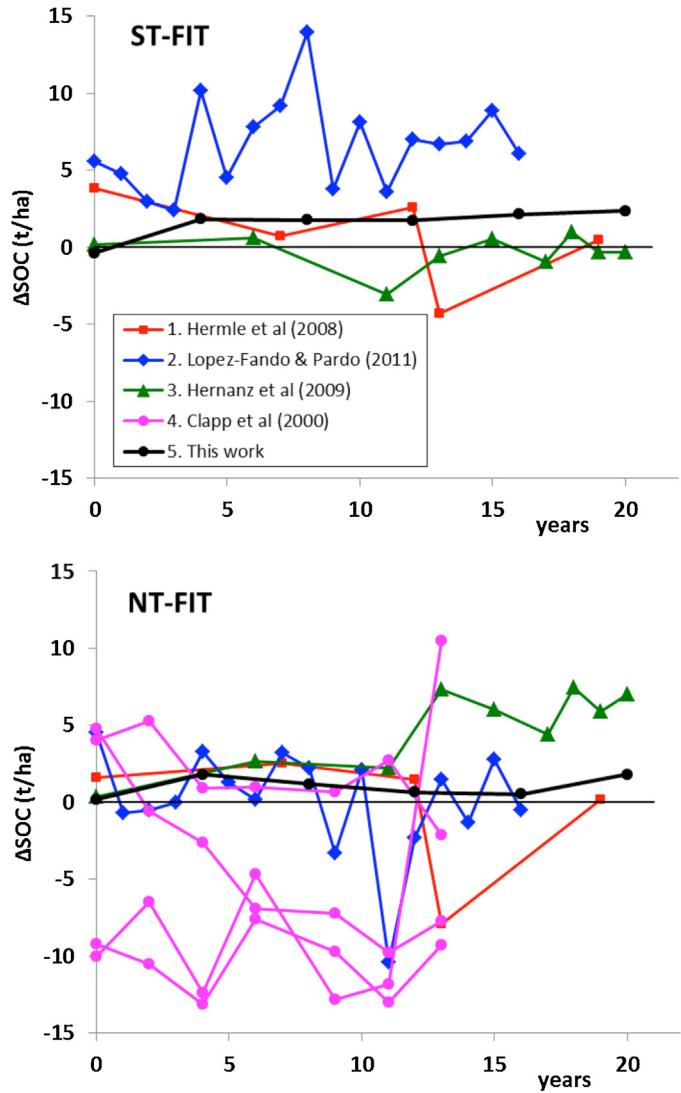


**Fig. 5.** Relationship between the rate of change in SOC content (between two successive dates of measurement) and the water balance during the same period, in the upper layer (0–5 cm) of NT treatment. Water balance is defined as  $P+I-PET$ , where  $P$  is the mean annual precipitation,  $I$  the irrigation and PET the potential evapotranspiration.

conducted by Angers and Eriksen-Hamel, 2008 who gathered 47 experiments with a mean duration of 16 years. They calculated a mean increase in SOC concentration of 19% in 0–10 cm and a mean decrease of −13% in 10–30 cm. These values are close to ours: +23% and −13% respectively after 12 years. This stratification appears to be a very general pattern in all reduced tillage systems over the world.

#### 4.2. Capturing dynamics of SOC sequestration with time series analyses

The studies involving time series analysis like ours should allow a precise estimate of the rate and duration of C sequestration and provide clues to understand its determinism. We selected long-term studies comparing FIT and ST or NT treatments fulfilling four conditions: (i) duration greater than 10 years; (ii) initial conditions measured in all plots; (iii) sampling depth at least equal to the current ploughing depth and (iv) time series of SOC stocks based on measurements of SOC concentrations and bulk densities. Four studies were identified: Clapp et al., 2000, Hermle et al., 2008,



**Fig. 6.** Differences in SOC between reduced tillage (ST or NT) and full inversion tillage (FIT) versus time in five long-term experiments providing a SOC dynamics. Soil depth = 30 cm in references 2, 4 and 5 and 40 cm in references 1 and 3.

Hernanz et al., 2009 and López-Fando and Pardo, 2011. We calculated the  $\delta\text{SOC}$  stocks over time (differences NT-FIT and ST-FIT) in these studies and reported them in Fig. 6, including our results during the first 20 years. The results show rapid inter-annual variations which are likely to be due, at least partially, to spatial variability. They also indicate that the Y intercept can widely differ from 0, due to soil heterogeneity between treatments at time 0. The more regular pattern of  $\delta\text{SOC}$  versus time found in our experiment is attributed to a lower spatial variability due to a greater sampling density, each point being the mean of 8–24 replicated plots with replicates within plots and to an excellent homogeneity at time 0. The evolution of  $\delta\text{SOC}$  did not show any curvilinear trend, so that we calculated linear regressions. The slope of the regressions significantly differed from 0 in one case out of four in ST and in four cases out of nine in NT. One slope was positive in ST and one in NT, whereas two slopes were negative in NT. On average in these long-term experiments, with time series data, reduced tillage did not result in C sequestration compared to full inversion tillage. We conclude that spatial variability often exceeds the temporal variation of SOC, hampering our capacity to draw reliable conclusions on the rate and intensity of C sequestration. New time

series must aim at a better compromise between spatial sampling (density) and temporal sampling (frequency).

#### 4.3. SOC dynamics influenced by C inputs

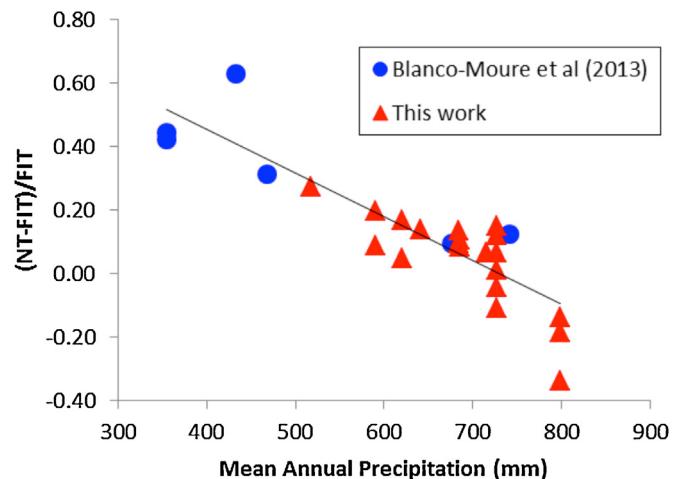
The amount of C input is known to be an important factor determining the changes in SOC stocks (e.g. Luo et al., 2010b). Our results dealing with SOC dynamics in the various crop management treatments are fully consistent with this assumption, as shown in four cases:

- (1) in crop management CM1, the amount of crop residues increased by 22%, 33% and 44% during the second, third and fourth period, relatively to the first period (1970–1982). The increase in SOC stocks in FIT throughout time (see Fig. 3), although not significant, is well correlated to this increase.
- (2) the conversion of maize/wheat rotation to the 4 years rotation resulted in a mean SOC decline of  $2.3 \pm 1.0 \text{ t ha}^{-1}$ , which is related to lower amounts of crop residues.
- (3) the establishment of catch crop led to higher SOC stocks, although not significantly different. The mean gain,  $1.3 \pm 1.4 \text{ t ha}^{-1}$ , obtained after 9 years, compares favorably with the review of Justes et al., 2012 who reported a C sequestration ranging from  $0.15$  to  $0.30 \text{ t ha}^{-1} \text{ yr}^{-1}$ .
- (4) after 12 years of crop residues removal (CM6), SOC stocks remained stable and became 5.5, 10.7 and 8.8% lower than those of CM1 in 1994 in FIT, ST and NT, respectively, due to the fact that the amount of crop residues was reduced by 66%.

Powlson et al., 2011a examined data from 23 long-term straw incorporation experiments from 6 to 56 years old, and found a reduction in SOC concentrations in the majority of experiments when straw was removed every year. In Rothamsted and Woburn experiments (UK), straw removal during 22 years led to a 5–10% decrease in SOC concentration in the top soil (23 cm) compared to straw addition at normal rate (S1:  $5 \text{ t ha}^{-1} \text{ yr}^{-1}$ ). The effect of tillage on SOC stocks can also be related to the possible variation in yields and C inputs. Virto et al., 2012 showed, in their meta-analysis, that the C input coming from crop residues is the major factor that significantly correlates with the differences in SOC stocks between NT and FIT, explaining 30% of their variability. In our study, we found that crop yields were dependent on crop management but not on tillage treatment, which suggests that tillage treatments produced similar C inputs, dismissing the hypothesis of differences in SOC due to differential C inputs.

#### 4.4. SOC dynamics influenced by climate $\times$ tillage interaction

An important drop was observed in SOC stocks between 1998 and 2002, ranging from  $-2.3$  to  $-4.8 \text{ t ha}^{-1}$  over the old ploughed layer. This drop was systematic in reduced tillage treatments in all crop managements under the maize/wheat rotation, indicating that it was a true effect not related to sampling uncertainty. We found that this drop, and more generally the SOC variations during the 4 years preceding soil samplings, were significantly correlated to the water balances. The better correlation was found in the upper layer of the NT treatment. These results can be attributed to an increase in soil water contents during the wet years and/or irrigated crops which enhances soil organic matter decomposition under reduced tillage, particularly in surface soil where most crop residues are located and where water contents may vary rapidly. Conversely, dry years allow C sequestration in reduced tilled system due to a greater reduction in SOC mineralization compared to FIT. The climate  $\times$  tillage interaction that we identified thanks to our diachronic analysis is consistent with the result of other synchronic studies. Campbell et al., 2005 showed that the rate



**Fig. 7.** Relative difference between no-tillage (NT) and full inversion tillage (FIT) in SOC stocks at 0–5 cm soil depth versus mean annual precipitation. Blue circles: results of Blanco-Moure et al., 2013 in five sites in Aragon (Spain) after 9–20 years; red triangles: results of this work (each point corresponds to a 4 years period). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

of gain in soil C was greater for no-till than for tilled systems in dry regions, such as those in western Canada. Gregorich et al., 2009 suggested that C storage potential in eastern Canada was dependent on the interaction between climate and type of primary tillage. In Australian agrosystems, Luo et al., 2010b reported that SOC increase due to conservation tillage was much smaller in sites where annual precipitation exceeded  $600 \text{ mm yr}^{-1}$  compared to sites with  $400$ – $600 \text{ mm yr}^{-1}$ . Blanco-Moure et al., 2013 calculated the relative difference in SOC stocks between NT and FIT treatments ( $\delta\text{SOC}$ ) in five sites in Aragon (Spain) after 9–20 years. They observed a significant negative relationship between  $\delta\text{SOC}$  in the 0–5 cm layer and the mean annual precipitation in each site, varying from  $355$  to  $740 \text{ mm yr}^{-1}$  (Fig. 7). Our data calculated similarly every 4 years could be added on the same figure and followed the same trend, confirming their findings. We conclude that the climate interacts with tillage, leading both to a greater C sequestration potential in drier than in wetter regions and an additional source of variability in the estimates of C sequestration due to reduced tillage.

#### 4.5. SOC dynamics affected by depth in reduced tillage systems

We observed a rapid sequestration of SOC in soil surface (0–10 cm) in the reduced tillage treatments. The steady state at soil surface seems to appear after about 24 years but the response time is rather inaccurate due to SOC fluctuations which are due to climate variations and spatial variability. West and Post, 2002 calculated that C sequestration rates can be expected to reach peak sequestration rates in 5–10 years, and decline to near zero in 15–20 years. Hernanz et al., 2009 evaluated SOC variations in three tillage systems over 20 years and concluded that the steady state of SOC sequestration was reached after 11 years in NT. In fact, the analysis of the SOC evolution in the 0–10 cm layer suggests that steady state could be attained after 17 years in this experiment and 13 years in the study of López-Fando and Pardo, 2011.

In the deeper layers (ca. 15–28 cm), we found a low and continuous loss of carbon in reduced tillage treatments. The mean rate of change was  $-0.07 \pm 0.04$  and  $-0.08 \pm 0.02 \text{ t yr}^{-1}$  (mean and confidence interval of the slope of the linear regression) for ST and NT respectively, leading to a loss of 17% and 18% of initial soil carbon after 41 years. Similar results were obtained in the previously cited experiments. Hernanz et al., 2009 found a rate of

$-0.09 \pm 0.04$  and  $-0.09 \pm 0.07 \text{ t C yr}^{-1}$  in layer 20–30 cm, leading to a loss of 23% after 20 years. López-Fando and Pardo, 2011 reported a rate of  $-0.18 \pm 0.17$  and  $-0.22 \pm 0.18 \text{ t C yr}^{-1}$  in layer 20–30 cm and 35–44% decrease in SOC resp. after 16 years. In the Rosemount experiment (USA) investigating tillage, crop residue and N fertilization, Clapp et al., 2000 found a decay rate of  $-0.33$  to  $-1.28 \text{ t yr}^{-1}$  in the layer 15–30 cm, corresponding to 7–30% SOC loss in 13 years. These high net decay rates (7–44%) question the commonly reported idea that no-tillage markedly reduces the C mineralization rate in the lower, undisturbed soil layers, due to physical protection. Such time series studies are the unique means to determine the *in situ* C mineralization rates as affected by tillage, at least if we can estimate C inputs in these layers.

## 5. Conclusion

This study emphasizes the interest of diachronic studies which consider land management history, initial conditions and SOC evolution in order to better understand the drivers of SOC dynamics as affected by tillage and crop management. Only long-term experiments with time series allow testing the consistency of SOC changes versus time. Our study confirmed that reduced tillage induced a pronounced stratification of SOC concentrations over the soil profile and that this stratification increased with time, both by continuous accumulation at soil surface and decrease in depth. It confirms the importance of deep sampling for comparing tillage treatments and avoiding misinterpretations (Baker et al., 2007). We found that crop management such as residues removal, crop rotation and catch crops play an important role in C sequestration, at least equal to soil tillage. Although SOC stratification within the soil profile due to reduced tillage can affect soil properties (pH, moisture content, bulk density) and processes controlling SOC dynamics (nutrients availability, microbial diversity, priming effect, ...) in each layer, the global effect of reduced tillage on SOC stocks was nil after 40 years. We showed that C sequestration due to reduced tillage may follow a non-monotonic evolution, increasing and decreasing in relation with the water balance. Further investigations are required to better qualify the interactions between variations in total SOC, greenhouse gas balance, tillage and climatic conditions.

## Acknowledgments

This study has been made possible thanks to the financial support of Arvalis-Institut du Vegetal and ANRT. We acknowledge P. Boillet, S. Bureau, D. Gaudillat and A. Geille for their participation in the management of the long-term experiment. We are grateful to D. Boitez, N. Collanges, C. Dominiarczyk, E. Gréhan, C. Ramelet, A. Teixeira, P. Thiébeau and E. Venet for their valuable assistance in soil sampling and preparation, O. Delfosse and L. Dixon for the analyses and J. Duval for the database management.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.agee.2014.02.014>.

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