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Alternative arable cropping systems: A key to increase soil organic carbon storage? Results from a 16 year field experiment

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ABSTRACT

Alternative cropping systems such as conservation agriculture and organic farming are expected to decrease negative impacts of conventional systems through sequestration of organic carbon in soil and mitigation of greenhouse gas emissions. We studied soil organic carbon (SOC) dynamics in the long-term (16 years) field experiment "La Cage" (France) which compares four arable cropping systems, free from manure application, under conventional (CON), low input (LI), conservation agriculture (CA) and organic (ORG) management. Bulk densities and SOC concentrations were measured at different dates between 1998 and 2014. SOC stocks were calculated at equivalent soil mass taking into account bulk density variations and SOC redistribution across the different soil layers. We analyzed the evolution of SOC stocks and compared it with outputs of the simulation model AMG. The rate of change in SOC stocks in the old ploughed layer (*ca.* 0–30 cm) during the 16 years was 0.08, 0.02, 0.63 and 0.28 t ha^{-1} yr^{-1} in the CON, LI, CA and ORG systems respectively and significantly differed from 0 in the CA and ORG treatments. The AMG model satisfactorily reproduced the observed evolution of SOC stocks in the old ploughed layer in all treatments. A Bayesian optimization procedure was used to assess the mean and the distribution of the most uncertain parameters: the SOC mineralization rate and the C inputs derived from belowground biomass of cover crops which were fescue (*Festuca rubra*) and alfalfa (*Medicago sativa*). The model thus parameterized was able to predict SOC evolution in each block and soil layer (0–10, 10–20 and 20–30 cm). There was no significant difference in SOC mineralization rates between all cropping systems including CA under no-till. In particular, the increased SOC storage in CA was explained by higher carbon inputs compared to the other cropping systems (+1.72 t C ha^{-1} yr^{-1} on average). The CA and ORG systems were less productive than the CON and LI systems but the smaller C inputs derived from cash crop residues were compensated by the extra inputs from additional crops (fescue and alfalfa) specifically grown in CA and ORG, resulting in a positive carbon storage in soil. We conclude that alternative arable systems have potential to sequester organic carbon in temperate climate conditions, through higher carbon input rather than by the effect of reduced soil tillage.

1. Introduction

Soil is one of the major components of the biosphere, delivering various essential ecosystems services. It constitutes the main terrestrial carbon sink, containing 1500 Gt of carbon across one meter depth (Batjes, 1996). Farming practices impact this compartment through modification of carbon inputs coming from crop residues or organic fertilizers and indirectly by affecting soil organic carbon (SOC) turnover through soil disturbance. Optimized farming practices with high organic inputs, permanent plant cover and reduced soil tillage can play an essential role in soil carbon sequestration, defined by difference with a reference cropping system (*e.g.* Luo et al., 2010a), and thus in mitigating climate changes (West and Post, 2002; Freibauer et al., 2004; Powlson et al., 2011). Combining these practices can generate alternative cropping systems differing from the dominant paradigm of conventional systems as they share similar inspirations such as

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sustainable development of agriculture with the improvement ofenvironmental performance (Beus and Dunlap, 1990).

During the last twenty years, alternative cropping systems have been tested including some which may be less profitable for farmers (Eltun et al., 2002). Conservation, organic and integrated agriculture are examples of alternative systems with expected environmental benefits, including a greater soil organic carbon sequestration, depending on the implemented practices. Conservation agriculture is characterized by the suppression of soil tillage, more diversified crop successions and permanent plant cover. No-tillage systems are often included in this category (Corsi et al., 2012), although they often do not fulfill the last two criteria. Another alternative cropping system is organic agriculture which aims at minimizing its impact on soil, water and air quality. Systemic prevention of weeds, pests and diseases, combined with nutrient self-sufficiency is the core of sustainable organic production (Lammerts van Bueren et al., 2002) since external inputs should be limited (Watson et al., 2002). In such a farming system, crop production is mainly based on organic fertilizers (*i.e.* manure, compost), green manures and frequent tillage most often essential to control weeds. Low input system, also known as integrated system, combines some practices applied in organic or conservation systems, as it promotes natural regulation in the farming system in order to limit the use of external inputs and sustain farm income (Eltiti, 1992). Overall, reduced intensity in soil tillage, reduced and better adjusted fertilization, increased frequency of cover crops and weaker use of pesticides are the main features that distinguish alternative from conventional system.

Existing reviews on SOC storage in alternative *vs* conventional systems report contradictory results. They can arise from the difficulty of fulfilling all methodological requirements such as measurements of the initial state, measurements of C concentration and bulk density at a sufficient depth (at least 0–30 cm in order to include variation of the ploughing depth in the time) in order to calculate SOC stocks at equivalent soil mass between different dates. Higher SOC stocks were recorded in some studies dealing with cropping systems similar to conservation agriculture in which ploughing was stopped and the number of crops increased in the rotation for a same duration (West and Post, 2002; Calegari et al., 2008). However, recent *meta*-analyses selecting studies conducted with an adequate methodology revealed that SOC sequestration potential in no-till systems had been over-estimated (Luo et al., 2010a; Virto et al., 2011). Concerning organic cropping systems, several studies agreed on their ability to store more SOC than conventional ones (Mondelaers et al., 2009; Leifeld and Fuhrer, 2010; Gomiero et al., 2011; Gattinger et al., 2012; Tuomisto et al., 2012). These authors mainly attributed the extra C storage to a greater application of livestock manure in the organic systems. However, Leifeld et al. (2013) indicated that the proportion of conventional and organic systems in the *meta*-analysis of Gattinger et al. (2012) was unbalanced in terms of systems with external carbon inputs (27% and 92% respectively), leading to a misinterpretation. Since organic fertilizer (including manure) addition rate is a major driver of SOC sequestration, its uneven distribution makes the comparison between organic and conventional systems difficult and hampers the identification of possible other drivers, such as crop rotation and nature of carbon inputs (Leifeld et al., 2009). Finally, the number of experiments comparing conventional and alternative arable systems without livestock manure is scarce.

Here, we studied a long term experiment (16-yr) including four purely arable cropping systems without manure fertilization. Our objectives were to: i) compare SOC stocks in these systems; ii) predict the dynamics of SOC stocks with a simulation model and iii) understand the drivers of C storage with the help of modelling. The evolution of SOC stocks between 1998 and 2014 was simulated using the simple AMG model (Saffih-Hdadi and Mary, 2008). We tested two hypotheses: i) SOC stocks can evolve differently due to variations in carbon inputs between cropping systems and ii) the mineralization rate of SOC is unaffected by the type of cropping system.

2. Materials and methods

2.1. Site and soil characteristics

The study was conducted at the long-term experimental site of “La Cage”, Versailles, France (48°48′N, 2°08′E) established in 1998 by INRA. Before 1998, the whole site was conducted under a conventional management. The purpose of the experiment is to evaluate the agronomic, economic and environmental performances of three alternative systems compared to a conventional cropping system which is representative of arable farming in Northern France. During the studied period (1998–2014), the mean annual temperature, precipitation and potential evapotranspiration were 11.3 °C, 627 and 673 mm respectively. The soil is a well-drained deep Luvisol (IUSS Working Group WRB, 2006) (Table 1). Minimum and maximum clay content varies between 150 and 184 g kg^{-1}, with a mean value of 167 g kg^{-1} over the whole field. In 1998, at the start of the experiment, the ploughed layer (0–25 cm) had a mean organic C content of 9.49 g kg^{-1}, a C:N ratio of 9.6 and a pH of 7.38.

2.2. Cropping systems

Four cropping systems are compared: a conventional (CON), a low input (LI), a conservation agriculture (CA) (direct seeding with permanent plant cover called cover crop) and an organic farming (ORG) system. The experimental site is divided in two blocks. Each block consists of four plots, each plot corresponding to one

Table 1
Physical and chemical properties of the soil at “La Cage” (layer 0–25 cm) measured at the start of experiment in 1998.

Cropping system	Block	Clay	Fine silt	Coarse silt	Fine sand	Coarse sand	Org. C	Total N	CaCO3	pH_{H2O}	CEC
		<2 μm	2–20	20–50	50–200	200–2000					
		(g kg^{-1})									(cmol+ kg^{-1})
CON	1	184	175	413	205	25	9.90	1.01	2.50	7.55	12.35
	2	171	202	408	195	25	9.30	0.92	0.83	7.40	11.55
LI	1	153	178	329	291	49	11.55	1.18	0.67	7.45	12.60
	2	165	197	432	184	23	9.15	0.93	0.50	7.05	10.10
CA	1	150	173	303	312	64	11.05	1.12	0.83	7.35	11.30
	2	174	186	404	213	25	9.55	0.97	0.83	7.35	11.15
ORG	1	177	181	411	208	24	9.45	0.94	0.33	7.35	11.50
	2	161	165	342	282	51	8.90	0.90	0.67	7.50	11.60

CON = conventional, LI = low input, CA = conservation agriculture, ORG = organic farming.

cropping system. The plots are divided into two subplots of 0.56 ha, each of them supporting a different crop of the rotation. Wheat is grown every year in one of the two subplots. A detailed presentation of crop rotations, soil management and fertilization in each treatment is given in Table 2. Each cropping system had its own management specificity:

1) Tillage. Ploughing occurred every year in CON and ORG, except after pea crops, and one out of two years in LI, before pea and rapeseed. No tillage was done in CA.
2) Fertilization. N fertilization varied every year according to crop and system. The mean amount of mineral N fertilizer applied over the 16 year period was 143, 114, 104 and 0 kg N ha^{-1} yr^{-1} for CON, LI, CA and ORG, respectively. No manure or external organic fertilizer was applied in the experiment, except in ORG in the first cropping period before 2009, during which guano and feather meal were used which represented 10 kg N ha^{-1} yr^{-1} on average. P and K were provided to all cropping systems except ORG through the application of mineral fertilizers.
3) Crop protection. A systematic use of pesticides was done in CON in order to avoid any yield limiting factor, whereas their application was made in LI and CA only when the damage threshold was exceeded. No pesticides were used in ORG, according to the European specifications for organic farming.
4) Rotation. A four year rotation was applied in the CON and LI systems during the whole period, 1998–2014: rapeseed (*Brassica napus* L.), winter wheat (*Triticum aestivum* L.), spring pea (*Pisum sativum* L.) and winter wheat. The rotation was modified in the CA and ORG systems because of a progress strategy and the integration of technical innovation. Additional main crops differed according to the treatment: maize (*Zea mays* L.) grown two years in CA instead of rapeseed, and alfalfa (*Medicago sativa*) in CA and ORG.
5) Crop residue management. Main crops were harvested for grain at maturity and crop residues were left at soil surface for all of the treatments. Alfalfa was cut three to four times per year in ORG and CA and left on soil surface as a green manure except for the first cut which was removed from the plots in ORG. Catch crops, grown during fall and winter between two main crops in order to avoid nitrate losses, were oat (*Avena sativa* L.), vetch (*Vicia sativa* L.), white mustard (*Sinapis alba* L.) and fodder raddish (*Raphanus sativus* L.). Cover crops, grown only in CA under the main crop in order to protect the soil, were alfalfa and fescue (*Festuca rubra*). Cover and catch crops grown in CA were chemically destroyed or rolled before seeding the cash crop.

The frequency of occurrence of the various crops (main crops, catch crops and cover crops) from 1998 to 2014 varied among the four cropping systems (Fig. 1). Winter wheat frequency was about 50% in each cropping system in order to be representative of regional practices. Winter rapeseed and spring pea were less represented in CA and ORG than in CON and LI systems, but CA and ORG included a significant proportion of alfalfa (18% and 34% respectively) which did not appear in the other systems. The specificity of the CA system was its higher frequency of catch crops and above all the presence of a cover crop.

2.3. Crop yields and residue biomass

Crop yields were determined every year from 1998 to 2014 based on grain collected by the combine harvester. The biomass of aboveground (AG) residues of the main crops returned to soil was estimated using the harvest index of each crop which was 0.54, 0.60, 0.31 and 0.46 for wheat, pea, rapeseed and maize respectively (Beaudoin et al., 2008) The AG biomass of catch crops and cover crops totally returned to soil was not measured but estimated using crop growth allometric equations (see Appendix A). It was assessed using a relationship based on the thermal time, *i.e.* the cumulative temperature above the crop base temperature. In the case of alfalfa as main crop, the exported cut was measured at mowing time and the cuttings left on the soil were estimated using regional references. When alfalfa was grown as cover crop, we used relationships depending on the date of cutting and regrowth: one for the period of establishment after seeding at the end of summer, one for autumn regrowth and the last for spring and summer regrowth.

Belowground (BG) biomass was not quantified in the experiment. BG biomass of main crops was assumed to be independent of

Table 2
Crop rotations, soil tillage and nitrogen fertilization management at “La Cage” over the period 1998–2014.

Management		CON	LI	CA	ORG
Crop rotation	1998	pea	pea	pea (2)	wheat
	1999	wheat	wheat	wheat: fescue	rapeseed
	2000	rapeseed	rapeseed	corn: fescue	wheat
	2001	wheat	wheat	wheat: fescue (2)	pea
	2002	pea	pea	pea: fescue (2)	wheat
	2003	wheat	wheat	wheat (3)	alfalfa
	2004	rapeseed	rapeseed	corn (4)	alfalfa
	2005	wheat	wheat	wheat	wheat
	2006	pea	pea	pea	rapeseed
	2007	wheat	wheat	wheat	wheat
	2008	rapeseed	rapeseed	wheat: alfalfa	wheat
	2009	wheat	wheat	alfalfa	alfalfa
	2010	pea	pea	wheat: alfalfa	alfalfa
	2011	wheat	wheat	alfalfa: fescue	wheat
	2012	rapeseed (1)	rapeseed (1)	oat: alfalfa	wheat
	2013	wheat	wheat	alfalfa	alfalfa
	2014	pea	pea	wheat: alfalfa	alfalfa
Ploughing		each year	every 2 years	no till	each year
Nitrogen fertilization (kg N ha^{-1} yr^{-1})		143	114	104	10
Yield (t ha^{-1} yr^{-1})[a]	wheat	9.7	8.9	6.7	5.4
	pea	4.2	4.5	3.7	2.6
	rapeseed	4.5	3.8	–	0.8

When grown with a cover crop, main crop is followed by ":" and the name of the cover crop. Catch crop following a main crop is in brackets (1 = white mustard, 2 = oat and vetch, 3 = clover, 4 = oat). CON = conventional, LI = low input, CA = conservation agriculture, ORG = organic farming.

[a] Grain yields is given for comparison, at 15% moisture content.

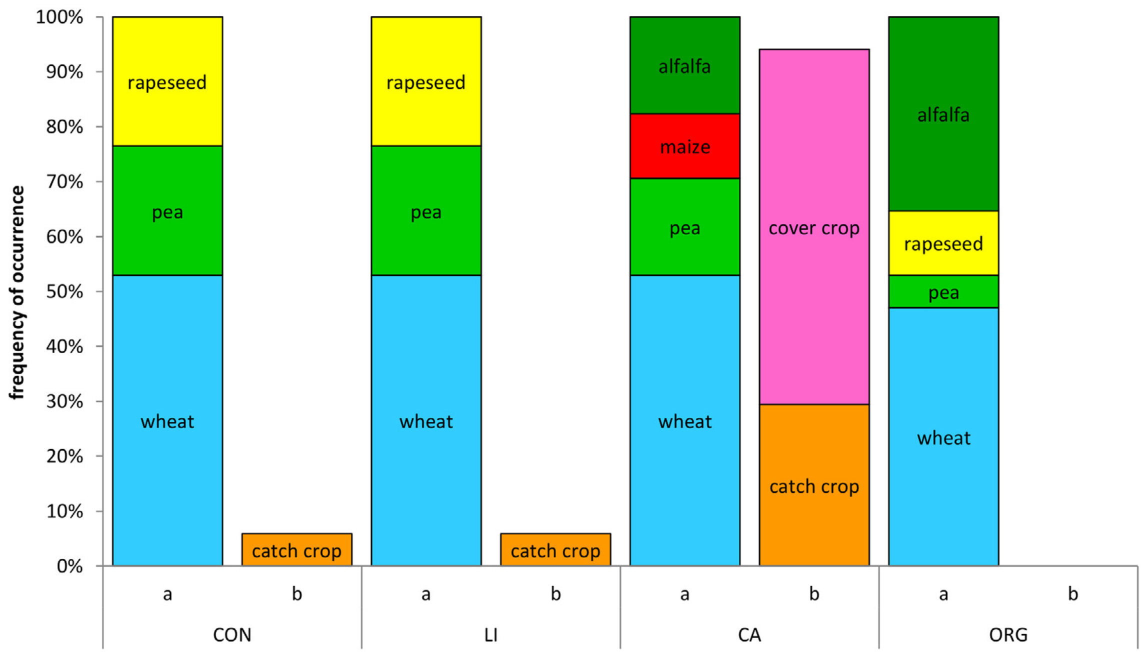

Fig. 1. Cumulative frequencies of occurrence of a) main crops and b) auxiliary crops in the 4 cropping systems (mean values over the period 1998–2014). CON = conventional, LI = low input, CA = conservation agriculture, ORG = organic farming.

AG biomass and calculated using references from Dubrulle et al. (2004): it was 2.33, 2.33, 0.98 and 2.24 t DM ha^{-1} for wheat, rapeseed, pea and maize respectively. In the case of catch crops and cover crops, we assumed that their BG biomass was proportional to their AG biomass because they derived from younger, unripe plants. The BG/AG ratio was set at 1.6 for fescue (Vertes et al., 2002), 0.6 for alfalfa (Thiebeau et al., 2011) and 0.7 for catch crops (Constantin et al., 2010). The conversion of dry mass to C content was made by assuming a 42% and 38% carbon content in the AG and BG residues, respectively (Justes et al., 2009).

2.4. Soil sampling and analysis

The soil sampling strategy was designed to calculate SOC stocks on an equivalent soil mass (ESM) basis (Ellert and Bettany, 1995) over a depth at least equal to the deepest tillage event. The ploughing depth was *ca.* 30 cm before 1998 and shallower afterwards, about 25 cm. The SOC measurements were carried out at the experimental site on both blocks in 1998 and 2014, and only in block 2 in 2000, 2003 and 2011. In February 1998, twenty soil samples were taken in each plot over 30 cm depth. In May 1998, March 2000, March 2003 and March 2011, six soil samples per plot were taken in block 2 down to 30 cm in plots where wheat was grown. In April 2014, six soil cores per plot were taken in both blocks down to 60 cm using a hydraulic gauge of 6 cm diameter. A single soil layer (0–30 cm) was analyzed for samples taken in February 1998, March 2000, March 2003 and March 2011. The soil cores were divided in 3 layers in May 1998 (0–10, 10–20 and 20–30 cm), and 5 layers in April 2014 (0–10, 10–25, 25–30, 30–35 and 35–60 cm). Soil was homogenized, coarse residues (>2 mm) and visible roots were removed by hand picking. Soil samples were oven dried for 48 h at 35 °C and sieved (2 mm). A soil subsample of 20 g was finely ground in a ball mill (PM 400, Retsch, Germany) and an aliquot taken for carbon analysis. The Dumas method was used for carbon analysis using an elemental analyzer (EURO EA, Eurovector, Italy). The $CaCO_3$ content was measured by acid decarbonation (NF ISO, 1995). Inorganic C represented on average 0.08 g C kg^{-1} (Table 1) and was substracted from total C to obtain the organic C.

Bulk density was measured for three layers (0–10, 10–20 and 20–30 cm) simultaneously with soil sampling in 1998, 2000, 2003 and 2011 using a steel cylinder of 98 cm^3 inserted vertically in the soil. Soil was weighed after drying during 48 h at 105 °C. The same method was used to determine the bulk density on the 0–5 cm layer in 2014. A second method was used in 2014 to measure the bulk density every 5 cm in the layers between 5 and 40 cm with a gamma-densitometer (LPC-INRA, Angers, France).

Coarse particulate organic matter (cPOM) was determined in soil samples taken in 2003 and 2014 by particle size separation. A sample of 50 g of 2 mm sieved and air dried soil was dispersed under water on a 200 μm sieve. Coarser particles (200–2000 μm) were washed out in a bucket, floating particles (cPOM) collected and oven dried at 60 °C before being crushed and analyzed for C concentration.

2.5. Calculations of soil mass and SOC stock

SOC stocks were calculated on ESM basis at different depths, particularly over the old ploughing depth, using measurement of bulk densities and organic C concentrations. To facilitate calculations, the soil was discretized into elementary layers of 1 mm thickness. The soil mass at a fixed depth z (in mm), $M(z)$ (in t ha^{-1}), can be calculated as the sum of soil masses of z elementary layers, as follows:

$$M(z) = 10\sum_{k=1}^{z}\rho(k) \quad (1)$$

where $\rho(k)$ is the bulk density of the elementary layer k (g cm^{-3}), k varying from 1 to 600 mm. A reference soil mass M_R (in t ha^{-1}) was considered, corresponding to the old ploughing depth of the CON system (30 cm) which was estimated in 1998 at 4300 t ha^{-1}. For the subsequent years, the z value corresponding to M_R was determined by fulfilling the equation: $M(z) = M_R$. We also considered three other soil mass references in order to analyze the SOC evolution in the soil profile: L1 (*ca.* 0–10 cm) and L2 (*ca.* 10–20 cm) with a fixed mass of 1300 t ha^{-1} for each layer, L3 (*ca.* 20–30 cm) with a fixed mass of 1700 t ha^{-1} of soil, L4 (*ca.* 30–40 cm) with a fixed mass of 1400 t ha^{-1} and L5 (*ca.* 40–60 cm) with a fixed mass of 2800 t ha^{-1}.

The cumulative SOC stock $QC(z)$ (in t ha^{-1}) in the layer 0-z is:

$$QC(z) = 0.01 \sum_{k=1}^{z} \rho(k).C(k) \quad (2)$$

where $C(k)$ is the SOC concentration in the elementary layer k (g kg^{-1} dry soil). Since the measured values of bulk densities and SOC concentrations refer to macro-layers (L1 to L5), $\rho(k)$ and $C(k)$ were supposed to be equal to their respective values in these macro-layers.

2.6. Statistical analysis

Statistical analyses were performed using the R software (R Core Team, 2014). Since the number of true replicates in the experiment was low (two randomized blocks), each of the two subplots (not randomized) was considered as replicate thus producing four pseudo replicates. This choice resulted from the weakness of the experimental design, which forces us to be conservative with our results as explained by Hurlbert (1984). Henneron et al. (2015) and Pelosi et al. (2015), analyzing the soil organisms on the same site, have described the rationale supporting this choice: i) the entire experiment had the same crop management before 1998, ii) soil sampling was done in large plots (0.56 ha) and samples were taken far enough from each other to be considered as independent, and iii) the preexisting topographic and pedologic gradients were controlled by blocking. Indeed, our measurements relative to SOC concentrations and stocks made in 1998 show that the intra-plot variability (between subplots) was as important as the inter-plot variability (within blocks), as indicated by the comparison of variances ($F = 1.83$, $p < 0.05$). Furthermore, our objective was to compare not only SOC stocks at given dates but also the temporal variations of SOC stocks between cropping systems. These variations, calculated as the difference between final and initial SOC stocks measured in each subplot, can be considered as true replicates, if we assume that possible interactions between the effect of cropping systems and the initial SOC stocks were of second order of magnitude.

Analyses of variance (ANOVA) were performed on measurements made in 1998, 2000 and 2014 to test the effect of cropping system on SOC stocks for all layers L1, L2, L3 and L1-3, and only on L1-3 for 1999, 2001, 2003 and 2011. A separate ANOVA was done to compare the SOC concentrations and stocks of 1998 and 2014 for each treatment and the change in SOC stocks between 1998 and 2014 for each treatment. The assumptions of ANOVA were checked by visually examining the residuals against predicted values and using the Shapiro-Wilk and Levene's tests. The existence of significant effects ($p < 0.05$) was followed by a post-hoc comparison test of means with the SNK.test from the *agricolae* package (De Mendiburu, 2014). When normality and homoscedasticity were not respected, a Kruskall-Wallis test was applied followed by means comparison using the kruskal.test from the *agricolae* package (De Mendiburu, 2014).

2.7. Simulation of SOC stocks evolution

2.7.1. AMG model

The simulation of SOC stocks evolution was made over the 1998–2014 period using the AMG model (Andriulo et al., 1999; Saffih-Hdadi and Mary, 2008). AMG is a simple soil simulation model with an annual time step, which considers three compartments of organic matter: crop residues, active and stable humified organic matter. AMG was successfully evaluated to simulate SOC evolution in Argentina (Andriulo et al., 1999; Milesi Delaye et al., 2013) and in 9 long term experiments (Saffih-Hdadi and Mary, 2008). The model uses the following equations:

$$QC = C_S + C_A \quad (3)$$

$$\frac{dC_A}{dt} = \sum_i m_i h_i - kC_A \quad (4)$$

where QC is the SOC stock (t ha^{-1}), C_S is the stable carbon stock (t C ha^{-1}), C_A is the active carbon stock (t C ha^{-1}), m_i is the annual carbon input of organic residue i (t ha^{-1} yr^{-1}), h_i is the humification coefficient of the residue i and k is the mineralization rate of the soil active fraction (yr^{-1}). In the case where carbon input rate is constant every year, equations (3–4) can be integrated as:

$$QC = C_S + (C_0 - C_S)e^{-kt} + \sum_i \frac{h_i m_i}{k}(1 - e^{-kt}) \quad (5)$$

where C_0 is the initial SOC stock (t ha^{-1}). The second term represents the residual amount of old carbon initially present and the third term is the humified carbon formed since the initial time. The mineralization rate k is dependent on pedoclimatic conditions and calculated as follows:

$$k = k_0.f(A).f(T) \quad (6)$$

where k_0 is the potential mineralization rate (yr^{-1}), A the clay content (g kg^{-1}) and T the temperature (°C). The functions and parameters are described in Saffih-Hdadi and Mary (2008).

2.7.2. Modelling steps

The evolution of SOC stocks of each cropping system was first simulated on block 2 in which SOC was measured more frequently than block 1. Required data for modelling were SOC stocks at different dates, carbon inputs from crop residues returned to the soil, clay content and mean annual temperature. Saffih-Hdadi and Mary (2008) proposed values for some of the parameters based on observations in long term experiments. They recommended a value of 65% for the Cs/Co ratio, which is the proportion of stable carbon in the soil, considered as equivalent in all the systems at the start of the experiment in 1998. They also proposed a humification rate for straw residues (h_a) with a value of 0.21 that we used here for all types of AG residues. The humification rate for BG residues (h_r) was set at 0.42, *i.e.* two times greater than for AG residues, in accordance with several studies showing that roots and rhizodeposits contribute more to humification than aboveground residues (Balesdent and Balabane, 1996; Clapp et al., 2000). Modelling was made in four steps:

Step 1: SOC stocks in layer L1-3 were simulated for each cropping system with default values of the model and compared with observed data (simulation S0). Using default parameters, we calculated the mineralization coefficient ($k = 0.044$ yr^{-1}), BG inputs from fescue residues in the CA system ($mf = 0.46$ t C ha^{-1} yr^{-1}), BG inputs from alfalfa residues ($ma = 0.58$ t C ha^{-1} yr^{-1} in CA and 0.44 t C ha^{-1} yr^{-1} in ORG system).

Step 2: the mineralization rate k of each of the four cropping systems was optimized, as well as the belowground inputs derived from fescue (mf) and alfalfa (ma), yielding six fitted parameters (simulation S6). The optimization procedure embedded in AMG software is based on a Bayesian method with a MCMC algorithm.

Step 3: the mineralization rate k was assumed to be the same in each cropping system and was optimized, as well as the mf and ma parameters, so that 3 parameters were optimized (simulation S3).

Step 4: the evolution of SOC stocks was simulated in layer L1-3 for block 1 and then for each layer (L1, L2 and L3) of block 2 using the values of k, mf and ma parameters obtained in simulation S3. In the case of the multi-layer simulation, the C inputs had to be allocated into each layer. We assumed that the C inputs derived from aboveground material were proportional to the amounts of cPOM measured in each layer. We tested two hypotheses concerning BG carbon inputs allocation among soil layers: i) an equal C input into each layer, ii) an allocation proportional to cPOM content.

The statistical criteria used to evaluate the model were the mean difference (*MD*) and the root mean square error (*RMSE*), both expressed in t C ha^{-1}:

$$MD_{jk} = \frac{1}{n_{jk}} \sum_{i=1}^{n_{jk}} (QC_{ijk} - \hat{QC}_{ijk}) \quad (9)$$

$$RMSE_{jk} = \sqrt{\frac{1}{n_{jk}} \sum_{i=1}^{n_{jk}} (QC_{ijk} - \hat{QC}_{ijk})^2} \quad (10)$$

where n is the number of observation for the treatments j and the layer k, QC_i and $\hat{QC}_i$ are the observed and estimated SOC stocks for the observation i, treatment j and layer k.

3. Results

3.1. Crop yields and residues

Mean wheat yields decreased in the following order: CON > LI > CA > ORG (Table 2). They varied between 9.7 t ha^{-1} yr^{-1} and 5.4 t ha^{-1} yr^{-1} and were strongly related to the mineral N fertilizer rate ($R^2 = 0.80$, $p < 0.05$). Pea yields were similar for CON and LI (4.3 t ha^{-1} yr^{-1} on average) and smaller in CA and ORG (3.1 t ha^{-1} yr^{-1} on average). Rapeseed yields were 4.5 and 3.8 t ha^{-1} yr^{-1} for CON and LI respectively and much smaller in ORG with 0.8 t ha^{-1} yr^{-1} (due to pest attacks) hence this crop was stopped after two years in ORG. The mean amount of AG residues from main crops (wheat, pea and rapeseed) was estimated at 7.1, 6.4, 4.9 and 3.6 t DM ha^{-1} yr^{-1} for CON, LI, CA and ORG respectively (results not shown). The estimated amounts of BG residues were less different between cropping systems, with a mean value of 1.9 t DM ha^{-1} yr^{-1}.

Details on carbon inputs from AG and BG residues are given in Table 3. The total inputs from the main crops varied between 1.80 and 4.03 t C ha^{-1} yr^{-1} and decreased in the following order: CON > LI > CA > ORG. Belowground inputs represented on average 0.71 t C ha^{-1} yr^{-1}, corresponding to 20% to 34% of the total inputs. Alfalfa as main crop was only cultivated in CA and ORG. The total inputs coming from this crop were estimated at 0.57 and 1.04 t C ha^{-1} yr^{-1} in CA and ORG respectively, the belowground material representing 29% and 45% of this input. Cover crops only concerned the CA system and consisted of fescue until 2009 and alfalfa since 2010. The estimated inputs from fescue were 0.88 t C ha^{-1} yr^{-1} and those coming from alfalfa as a cover crop were 1.12 t C ha^{-1} yr^{-1}, about half of these amounts deriving from root material. Catch crops grown in CA represented an additional input of 0.35 t C ha^{-1} yr^{-1}. Finally, total carbon inputs were higher in CA (5.41 t C ha^{-1} yr^{-1}) than in the three other systems which received 4.09, 3.81 and 2.87 t C ha^{-1} yr^{-1} for CON, LI and ORG respectively. Cover crops, catch crops and alfalfa biomass compensated for the lower main crop production in CA and ORG, since they contributed to 54% and 37% of the total C inputs.

3.2. Bulk densities

The measured bulk densities at the initiation of the experiment did not differ between plots, both in individual layers and in the old ploughed layer L1-3 (Table 4). There was also no significant difference between layers, unsurprisingly since the field was regularly ploughed (and therefore homogenized) down to about 30 cm before the onset of the experiment. In 2014, bulk density also did not differ between cropping systems both in individual layers and in layer L1. However a significant change occurred between 1998 and 2014. Bulk density increased in all layers and all treatments, even though the change was not significant in LI and ORG systems. The mean bulk density increased from 1.40 to 1.50 g cm^{-3}. The most detectable effect was found in the CA system where bulk density in the layers L2 and L3 was significantly greater than in the other systems, reaching 1.58 g cm^{-3}. This high value was compensated by a lower value in the upper layer, so that the mean value over the old ploughed layer was about the same in all systems. Bulk density values must be analyzed with care as they also vary within a year. However, bulk density evolution in CA system is consistent with an observation often made in no-till systems, *i.e.* a decrease in the upper layer (0–10 cm) and an increase below (10–30 cm) compared to conventional tilled systems (*e.g.* Dimassi et al., 2014).

3.3. SOC concentrations in 1998 and 2014

The profiles of SOC concentration among soil layers measured in 1998 and 2014 are presented in Fig. 2 for each cropping system. In 1998, no significant difference was found between systems

Table 3
Mean annual carbon inputs coming from crop residues (cash crops, cover crops and catch crops) over the 1998–2014 period.

		CON			LI			CA			ORG		
		AG	BG	AG + BG	AG	BG	AG + BG (t C ha^{-1} yr^{-1})	AG	BG	AG + BG	AG	BG	AG + BG
Main crop	Cash crops	3.23[a]	0.80[b]	4.03	2.95[a]	0.80[b]	3.74	1.84[a]	0.65[b]	2.50	1.19[a]	0.61[b]	1.80
	Alfalfa[c]							0.41	0.16	0.57	0.58	0.47	1.04
Cover crop[c]	Fescue[d]							0.39	0.49	0.88			
	Alfalfa[e]							0.70	0.42	1.12			
Catch crop[a,f]		0.04	0.03	0.07	0.04	0.03	0.07	0.21	0.14	0.35			
Organic residues[a,g]											0.02		0.02
Total inputs		3.27	0.82	4.09	2.99	0.82	3.81	3.55	1.86	5.41	1.79	1.07	2.87

AG = aboveground inputs, BG = belowground inputs. CON = conventional, LI = low input, CA = conservation agriculture, ORG = organic farming.
[a] Measured.
[b] Estimated with AMG model.
[c] Estimated by modeling (see Appendix A).
[d] Fescue, clover or fodder radish, period 1998–2009.
[e] Alfalfa, period 2010–2014.
[f] Oat and vetch, white mustard or fodder radish.
[g] Guano, feather meal.

Table 4
Bulk densities (g cm-3) measured in three soil layers in 1998 and 2014.

	Layer	Depth	ESM	CON			LI			CA			ORG		
		(cm)	(t ha^{-1})						(g cm^{-3})						
1998	L1	~0–10	1300	1.33	(0.03)		1.35	(0.07)		1.35	(0.04)		1.36	(0.08)	
	L2	~10–20	1300	1.41	(0.04)		1.43	(0.09)		1.39	(0.08)		1.46	(0.07)	
	L3	~20–30	1700	1.41	(0.04)		1.46	(0.06)		1.39	(0.08)		1.48	(0.08)	
	L1-3	~0–30	4300	1.38	(0.03)		1.41	(0.05)		1.38	(0.06)		1.43	(0.07)	
2014	L1	~0–10	1300	1.42	(0.09)	NS	1.43	(0.08)	NS	1.38	(0.02)	NS	1.50	(0.03)	*
	L2	~10–20	1300	1.52	(0.07)	*	1.53	(0.11)	NS	1.57	(0.02)	**	1.48	(0.02)	NS
	L3	~20–30	1700	1.54	(0.07)	*	1.55	(0.07)	NS	1.59	(0.03)	**	1.51	(0.01)	NS
	L1-3	~0–30	4300	1.49	(0.07)	*	1.50	(0.08)	NS	1.51	(0.02)	**	1.50	(0.01)	NS

Values in brackets are standard deviations. No significant differences were found between treatments, either in 1998 or in 2014. Asterisks indicate significant difference between years (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; NS = not significant). CON = conventional, LI = low input, CA = conservation agriculture, ORG = organic farming.

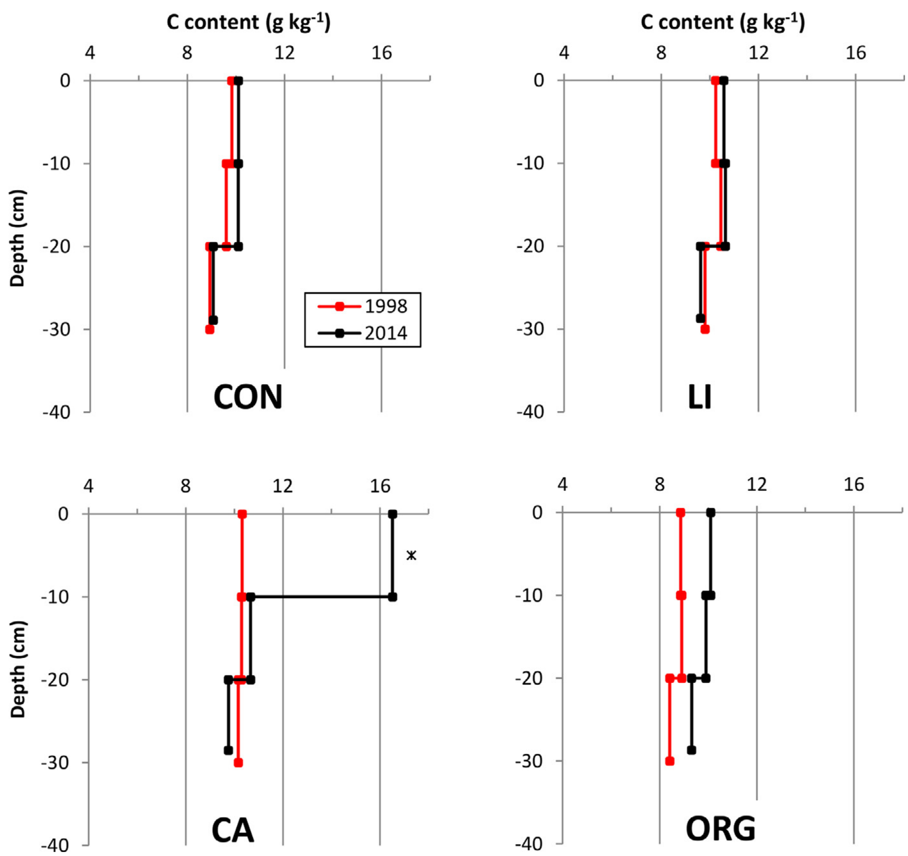

Fig. 2. Profile of carbon concentration in the soil in 1998 and 2014. Depths correspond to fixed equivalent soil masses (see Table 4). Asterisks indicate significant evolution between 1998 and 2014 (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$). CON = conventional, LI = low input, CA = conservation agriculture, ORG = organic farming.

except for ORG. The initial SOC concentration in ORG was smaller than in the other cropping systems (8.70 g kg^{-1} *vs* 9.76 g kg^{-1} on average, $p < 0.10$). In 2014, the distribution varied between the four cropping systems. SOC concentration in the first layer did not differ significantly between CON, LI and ORG (mean value = 10.2 g kg^{-1}), but was 61% higher in the CA system (16.5 g kg^{-1}, $p < 0.001$). No significant difference was found between cropping systems in any of the deeper layers (L2, L3, L4, L5). The mean SOC concentration in these layers was 10.5, 9.5, 5.3 and 4.1 g kg^{-1}, respectively. Over the whole ploughed layer (L1-3), CA had a significantly higher carbon concentration compared to the three other systems (+22%, $p < 0.05$). This was also true for layer L1-5, equivalent to 0–60 cm, since SOC concentration was 19% higher in CA compared to the other systems ($p < 0.01$): 8.54 *vs* 7.14 g kg^{-1} respectively. A significant temporal change in SOC concentration was detected between 1998 and 2014 in the CA system on the L1 layer (+0.39 g kg^{-1}, $p < 0.05$) but neither in the other cropping systems nor in the other layers.

3.4. cPOM concentration in 2014

The distribution of coarse particulate organic matter measured in 2014 in soil layers L1, L2 and L3 is presented in Table 5. cPOM concentration did not differ between CON, LI and ORG systems in any layer. The mean value in the old ploughed layer (L1-3) was 0.44 ± 0.01 g C kg^{-1}. cPOM concentration was much more stratified in the CA system: it was significantly higher in CA than in CON, LI and ORG in the upper layer L1 (0.85 *vs* 0.51 g C kg^{-1} on average) and

Table 5
Particulate organic matter (POM) measured in 2014: carbon concentration (g C kg^{-1}) and proportion of total soil organic carbon (%SOC).

Layer	Depth	ESM	CON				LI				CA				ORG			
	(cm)	(t ha^{-1})	(g kg^{-1})			%SOC	(g kg^{-1})			%SOC	(g kg^{-1})			%SOC	(g kg^{-1})			%SOC
L1	~0–10	1300	0.55	(0.12)	b	5.4%	0.50	(0.09)	b	4.7%	0.85	(0.21)	a	5.1%	0.48	(0.11)	b	4.7%
L2	~10–20	1300	0.53	(0.17)	a	5.2%	0.51	(0.12)	a	4.8%	0.33	(0.09)	b	3.1%	0.54	(0.10)	a	5.5%
L3	~20–30	1700	0.31	(0.12)	a	3.4%	0.30	(0.07)	a	3.2%	0.18	(0.06)	b	1.8%	0.34	(0.07)	a	3.6%
L1-3	~0–30	4300	0.45	(0.13)	a	4.6%	0.42	(0.07)	a	4.2%	0.42	(0.10)	a	3.5%	0.44	(0.06)	a	4.5%

Values in brackets are standard deviations. Different letters indicate significant differences between cropping systems (Newman-Keuls, CI = 95%). ESM = equivalent soil mass, CON = conventional, LI = low input, CA = conservation agriculture, ORG = organic farming.

lower in layers L2 and L3. A full compensation occurred between layers since cPOM concentration in the old ploughed layer of CA system was equal to that of other systems: 0.42 ± 0.01 g C kg^{-1}. cPOM carbon concentration in layer L1-3 represented between 3.5% and 4.6% of SOC; this was comparable to previous measurements made in 2003 (Balabane et al., 2005) which varied between 2.8% and 5.0%. The rather low content of cPOM indicates a fast decomposition of crop residues in all soil layers and all systems including CA.

3.5. SOC stocks in 1998 and 2014

At the start of the experiment, SOC stocks did not differ significantly between plots in any layer ($p < 0.05$), but tended to be lower in the ORG plots. The mean SOC content in the ploughed layer (L1-3) was 40.8 t ha^{-1} (Table 6). In 2014, the average SOC stocks at ESM were significantly higher in CA than in CON, LI and ORG which did not differ from each other ($p < 0.05$). The mean SOC amount in layer L1-3 was 51.9 t ha^{-1} in CA and 42.5 ± 1.2 t ha^{-1} in the three other systems. The SOC stocks over a greater depth (*ca.* 0–60 cm, layer L1-5) also differed significantly with 72.6 t ha^{-1} for CA against 60.7 ± 2.1 t ha^{-1} on average for CON, LI and ORG ($p < 0.01$). The main difference occurred in the upper layer L1 which contained 21.5 t ha^{-1} in CA, *i.e.* 8.1 t ha^{-1} higher than in the other systems. No difference between systems was detectable in layers L2 and L3.

The temporal variation of SOC stocks between 1998 and 2014 in each block is given in Table 7. SOC stocks in block 1 were always higher than the corresponding ones in block 2 (average difference = 5.9 t C ha^{-1}). The SOC change after 16 years was very similar between blocks in spite of the initial heterogeneity in SOC stocks. The mean change was 1.3, 0.3, 10.0 and 4.4 t ha^{-1} in the CON, LI, CA and ORG systems, respectively. The SOC increase was significant only in CA and ORG systems. If we consider the conventional system as a reference, the mean rate of C sequestration was 0.55 t ha^{-1} yr^{-1} in the conservation agriculture system and 0.20 t ha^{-1} yr^{-1} in the organic system.

3.6. Simulating the evolution of SOC stocks in the old ploughed layer

Table 8 presents the results of the three steps of simulation (S0, S6, S3) in terms of parameter values and statistical criteria giving the quality of fit for SOC stocks in layer L1-3 of block 2. In simulation S0, the simulations were conducted with the default parameters of the model and with C inputs indicated in Table 3. The total C inputs ranged from 2.87 t C ha^{-1} yr^{-1} in the ORG system to 5.41 t C ha^{-1} yr^{-1} in the CA system. The simulation gave a good agreement with the observed measurements, since the mean difference did not exceed 1.64 t C ha^{-1} (in CA system), and the root mean square error (on average 1.69 t C ha^{-1}) was close to the mean standard deviation of measurements (2.10 t C ha^{-1}). The positive MD reveals a slight underestimate of observed values by the model, particularly for the CA system. In simulation S6, which included the optimization of six parameters, the quality of fit was slightly improved compared to simulation S0 but the improvement was small since the average MD was 0.27 t C ha^{-1} (instead of 0.85 in S0) and the average RMSE equaled 1.47 t C ha^{-1} (instead of 1.69). The Bayesian optimization procedure resulted in a modification of calculated inputs; it suggested that the belowground inputs derived from fescue (*mf*) had been underestimated in CA whereas those derived from alfalfa (*ma*) had been overestimated. However the confidence intervals of *mf* and *ma* were large and included the default values considered in simulation S0. The mineralization rates (*k*) optimized for each of the four cropping systems were smaller than the default value used in S0 (0.041 *vs* 0.044 yr^{-1}) and all contained within the confidence intervals. No significant difference was found between the *k* values of the four cropping systems.

These observations led us to simulation S3, in which a single mineralization coefficient was adopted for all treatments. This

Table 6
SOC stocks (t C ha^{-1}) measured in 1998 and 2014 in three soil layers (mean of the two blocks).

	Layer	Depth	ESM	CON				LI				CA				ORG			
		(cm)	(t ha^{-1})									(t C ha^{-1})							
1998	L1	~0–10	1300	12.8	(1.0)	a		13.3	(2.0)	a		13.4	(2.5)	a		11.5	(1.4)	a	
	L2	~10–20	1300	12.5	(1.0)	a		13.6	(2.7)	a		13.4	(1.7)	a		11.6	(1.4)	a	
	L3	~20–30	1700	15.2	(1.9)	a		16.7	(3.3)	a		15.1	(5.0)	a		14.3	(1.5)	a	
	L1-3	~0–30	4300	40.4	(3.5)	a		43.6	(8.0)	a		41.9	(8.7)	a		37.4	(4.3)	a	
2014	L1	~0–10	1300	13.1	(1.1)	a	NS	13.7	(1.9)	a	NS	21.5	(2.9)	b	*	13.1	(1.3)	a	NS
	L2	~10–20	1300	13.1	(1.4)	a	NS	13.8	(1.8)	a	NS	13.9	(2.0)	a	NS	12.9	(0.7)	a	NS
	L3	~20–30	1700	15.4	(2.0)	a	NS	16.3	(2.1)	a	NS	16.6	(2.2)	a	NS	15.8	(1.2)	a	NS
	L4	~30–40	1400	6.7	(1.0)	a		7.3	(1.4)	a		8.4	(1.1)	a		7.2	(1.2)	a	
	L5	~40–60	2800	10.7	(5.8)	a		11.8	(5.5)	a		12.2	(1.2)	a		11.4	(4.5)	a	
	L1-3	~0–30	4300	41.7	(4.2)	a	NS	43.9	(5.3)	a	NS	51.9	(6.6)	b	NS	41.8	(2.6)	a	NS
	L1-5	~0–60	8500	58.8	(5.8)	a		63.0	(5.5)	a		72.6	(7.0)	b		60.4	(4.5)	a	

Values in brackets are standard deviations. Asterisks indicate significant difference between years (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; NS = not significant). Different letters indicate significant differences between rotations (Newman-Keuls, CI = 95%). ESM = equivalent soil mass, CON = conventional, LI = low input, CA = conservation agriculture, ORG = organic farming.

Table 7
Changes in SOC stocks during the 1998–2014 period in the old ploughed layer (L1-3).

	CON			LI			CA			ORG		
	($t C ha^{-1}$)											
Block 1	2.5	(2.4)		−0.9	(3.0)		11.3	(3.5)		4.9	(1.9)	
Block 2	0.0	(1.5)		1.6	(1.7)		8.7	(2.7)		3.9	(1.8)	
All blocks	1.3	(1.2)	a	0.3	(2.0)	a	10.0	(2.2)	c	4.4	(1.0)	b

Values in brackets are standard deviations. Different letters indicate significant differences between cropping systems (Newman-Keuls, CI = 95%). CON = conventional, LI = low input, CA = conservation agriculture, ORG = organic farming.

simulation S3 gave a similar quality of fit compared to S6, with a slightly higher MD (0.34 *vs* 0.27 $t C ha^{-1}$ on average) and RMSE (1.56 *vs* 1.47 $t C ha^{-1}$). The optimized values of *mf* were higher than the default values (0.73 *vs* 0.49 $t C ha^{-1} yr^{-1}$), suggesting that the fescue grown as cover crop had an important root turnover and produced greater amounts of rhizodeposits than initially assessed. In contrast, the optimized values of *ma* inputs were very close to the default value (4% higher). The optimized mineralization rate *k* was slightly smaller than the default value (0.041 *vs* 0.044 yr^{-1}).

The temporal evolution of observed and simulated SOC stocks in CON, LI, CA and ORG systems in block 2 is presented in Fig. 3. The three simulations (S0, S6 and S3) could correctly reproduce the dynamics of SOC evolution between 1998 and 2014 in the four cropping systems. The variability of SOC measurements in the CON system was greater than in other systems and hampers the comparison between observed and simulated values. The three simulated kinetics were very close each other in the LI and ORG systems, and close to observed data. The poorer simulation was obtained in CA system with the direct simulation S0 which underestimated observations made in 2000, 2003 and 2011. The better agreement obtained with simulations S3 and S6 during the 16 year period is mainly due to the increased values of C inputs derived from the fescue cover crop.

3.7. Simulation of SOC evolution in block 1 and elementary layers of block 2

In the last step, we evaluated the ability of the model to simulate the SOC stock in the L1-3 layer of block 1 with the parameter values obtained in simulation S3 for block 2. Fig. 4 shows that the model succeeded rather well in predicting the SOC stocks in 2014 in spite of the spatial variability between blocks, except for the CON treatment which had a greater intra-variability. This result points out the interest of a detailed characterization of the spatial variability of SOC contents at time 0 in long term experiments. During the 16 year period, the observed rate of change in SOC stock (mean of two blocks) was 0.08, 0.02, 0.63 and 0.28 $t C ha^{-1} yr^{-1}$ for CON, LI, CA and ORG respectively. It is rather close to the simulated rate of change which was 0.30, 0.06, 0.63 and 0.39 $t C ha^{-1} yr^{-1}$ respectively.

We also evaluated the ability of the model to predict the evolution of SOC stock in each layer (L1, L2 and L3) of block 2. The mineralization rate was assumed to be similar in each soil layer and equal to the value determined in simulation S3 ($k = 0.041 yr^{-1}$). The C inputs derived from fescue and alfalfa (optimized values of *mf* and *ma* resulting from simulation S3) were distributed between the three layers according to each allocation hypothesis made earlier, *i.e.* C allocation either proportional to cPOM content or identical in each layer. Observed and simulated SOC stocks are presented in Fig. 5. The quality of fit was about the same for each hypothesis made for belowground inputs (results not shown). Measurements indicated that SOC stocks in layers L2 and L3 were almost stable in all systems. Simulations gave good results for all treatments and all layers, except for the layer L1 in the CON system and the layer L2 in the CA system, whose SOC concentrations were all slightly overestimated.

4. Discussion

The “La Cage” experiment is characterized by alternative cropping systems with specific crop rotations (*i.e.* with cover or catch crops), no use of livestock manure or other exogenous organic fertilizer and a mineral fertilization in CON, LI and CA. We compare our results here with other studies on similar farming practices and for soil measurements made at least over 0–30 cm depth.

4.1. Yields and inputs of crop residues

The main crop yields observed in CON were similar to the regional production levels for wheat, pea and rapeseed over the same period. In the LI system, characterized by reduced N fertilization (−21%), ploughing frequency and use of pesticides,

Table 8
Mean value of the default or optimized parameters (*ma*,*mf* and *k*) for the simulations (S0, S3 and S6) of SOC evolution between 1998 and 2014.

	Total C inputs	BG C inputs	Fixed or optimized parameters						Statistical criteria		
			mf		*ma*		*k*		MD	RMSE	SD
			($t C ha^{-1} yr^{-1}$)				(yr^{-1})		($t C ha^{-1}$)		
S0. Simulation with default parameters											
CON	4.09	0.82					0.044		0.43	2.24	2.02
LI	3.81	0.82					0.044		0.41	1.21	1.08
CA	5.41	1.86	0.49		0.58		0.044		1.64	2.06	3.93
ORG	2.87	1.07			0.47		0.044		0.91	1.25	1.38
S6. Bayesian optimization (6 parameters)											
CON	4.09	0.82					**0.051**	(0.037–0.070)	1.04	2.24	2.02
LI	3.81	0.82					**0.041**	(0.031–0.051)	0.00	1.39	1.08
CA	5.62	2.05	**0.80**	(0.18–1.67)	**0.47**	(0.07–1.57)	**0.037**	(0.015–0.076)	−0.04	1.49	3.93
ORG	2.70	0.98			**0.38**	(0.06–1.26)	**0.034**	(0.024–0.054)	0.08	0.76	1.38
S3. Bayesian optimization (3 parameters)											
CON	4.09	0.82					**0.041**	(0.035–0.051)	0.14	2.34	2.02
LI	3.81	0.82					**0.041**	(0.035–0.051)	0.12	1.31	1.08
CA	5.67	2.12	**0.73**	(0.28–1.19)	**0.60**	(0.19–1.14)	**0.041**	(0.035–0.051)	0.49	1.58	3.93
ORG	2.89	1.09			**0.49**	(0.14–0.85)	**0.041**	(0.035–0.051)	0.59	1.00	1.38

mf = mean annual belowground inputs derived from fescue, *ma* = mean annual belowground inputs derived from alfalfa. Fitted parameters are shown in bold types. Confidence intervals are in brackets. Statistical criteria: MD = mean difference, RMSE = root mean square error, SD = standard deviation. CON = conventional, LI = low input, CA = conservation agriculture, ORG = organic farming.

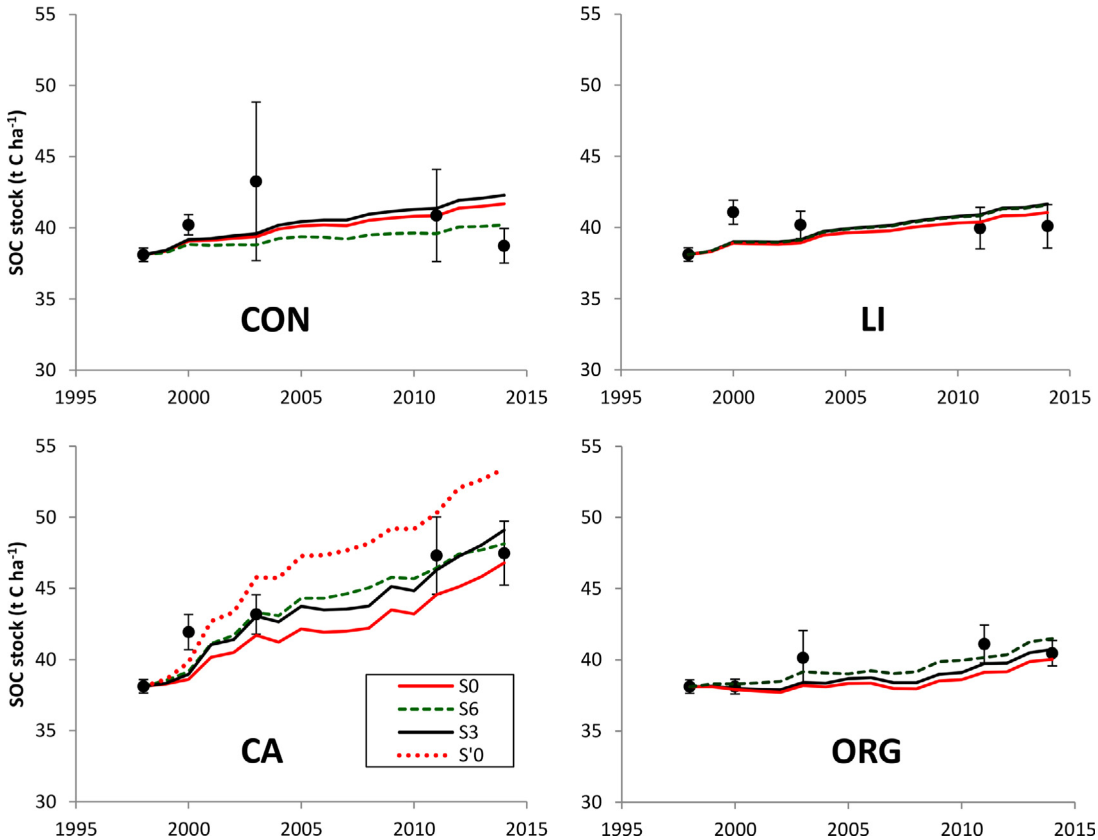

Fig. 3. Evolution of SOC stocks in the old ploughed layer (L1-3) from 1998 to 2014 in block 2: observed (symbols) and simulated values (lines) in the four cropping systems. S0 = simulation with original parameters; S6 = simulation with 6 parameters optimized; S3 = simulation with 3 parameters optimized (see Table 8); S'0 = simulation with a reduced mineralization rate in CA, according to Paustian et al. (2000). CON = conventional, LI = low input, CA = conservation agriculture, ORG = organic farming.

main crop yields were slightly smaller, with the average wheat yield reaching 91% of CON. Loyce et al. (2012) reported similar results for wheat grown under an integrated cropping system with management similar to LI in 28 field experiments in France between 1999 and 2002, with an average yield of 8.4 t ha^{-1} representing 94% of the conventional yield. In comparison, the ORG system which received neither mineral fertilizer nor farmyard

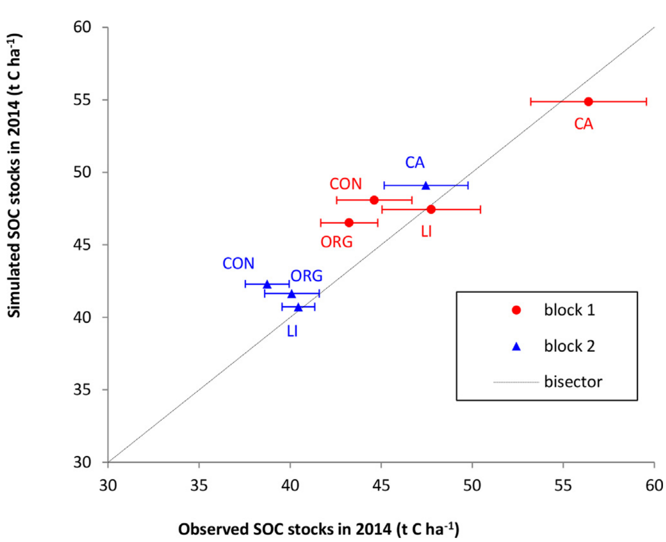

Fig. 4. Observed and simulated SOC stocks over the old ploughed layer (L1-3) in 2014 for each block and each cropping system. CON = conventional, LI = low input, CA = conservation agriculture, ORG = organic farming.

manure, wheat yields were much lower, averaging only 55% of CON. Entz et al. (2005) studied a similar organic system in a pure grain rotation, a green manure-grain rotation and an alfalfa-grain rotation without manure application for 12 years. Similar to our results, they found smaller yields in the organic compared to conventional system with a decrease of 63, 46 and 14% for the three rotations respectively. Seufert et al. (2012) reported in their *meta*-analysis that organic wheat yields reached 60% of conventional yields (75% when considering all cereals crops). Lastly, in our CA system, with a fertilization rate reduced by 28%, wheat yield represented 69% of the CON system. We compared these yields with two *meta*-analyses of observations made in no-tilled cropping systems, both showing a smaller gap with conventional yields. Firstly, the *meta*-regression carried out by Van den Putte et al. (2010) pointed out that yields of no-till systems in northern Europe were on average 8.5% lower than those obtained in conventionally tilled systems. Secondly, Pittelkow et al. (2015) found in their *meta*-analysis of 678 studies that cereal yields grown under no-till systems reached 95% of conventional yields.

Lower yields result in lower amounts of crop residues (aboveground + belowground) returned to soil which in turn affects SOC stocks. Thus, in our experiment, the estimates of total C inputs derived from cash crops ranked as follows: CON (4.03 t C ha^{-1} yr^{-1}) > INT(3.74) > CA (2.50) > ORG (1.80). However, the CA system is characterized by the frequent or permanent cultivation of catch crops and cover crops associated with the main crop. When also accounting for these additional crops, the C input ranking becomes: CA (5.41 t C ha^{-1} yr^{-1}) > CON (4.09) > LI (3.81) > ORG (2.87), revealing that the lower inputs associated with lower yields of the main crops were compensated by the inputs from cover crops, in particular from root materials. Bell et al.

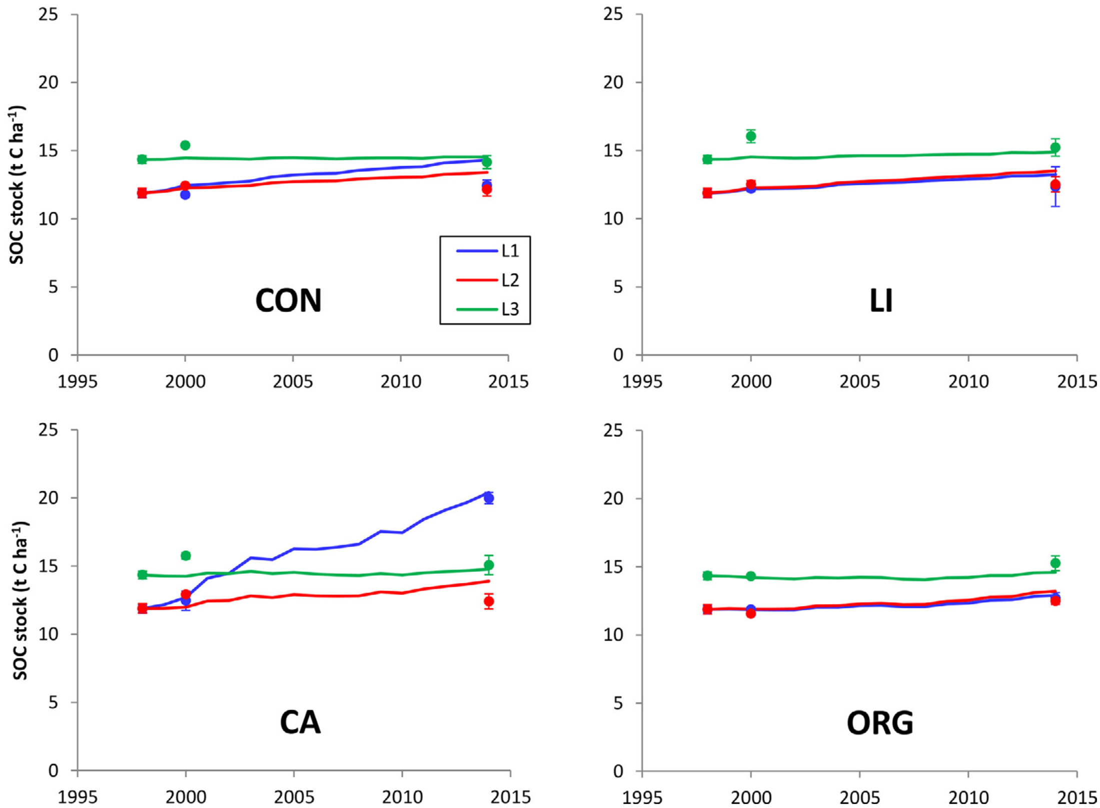

Fig. 5. Evolution of SOC stocks observed (symbols) and simulated (lines) from 1998 to 2014 in block 2 of each cropping system. Simulations correspond to S3 with optimized values of mf and ma and carbon input distribution in layers L1 (~0–10 cm), L2 (~10–20 cm) and L3 (~20–30 cm) proportional to cPOM concentration. CON = conventional, LI = low input, CA = conservation agriculture, ORG = organic farming.

(2012) estimated these inputs at 2.25 and 1.50 t C ha^{-1} yr^{-1} in their CON and ORG systems respectively, *i.e.* close to our values.

4.2. SOC storage in relation with cropping systems

The main change in SOC stock over the 16 studied years was found in the CA system (+10.0 t C ha^{-1}, *i.e.* +24%), followed by ORG (+4.4 t C ha^{-1}, *i.e.* +12%) whereas the other systems did not change significantly (+3% and +1% for CON and LI). The highest SOC increase observed in the CA system can be attributed to one or several specific practices: no-tillage, permanent soil cover and crop diversification. These effects are often reported separately by authors. However, the effect of tillage *sensu stricto* (all other factors being equal) on SOC sequestration is still controversial. In fact, the more recent *meta*-analyses comparing no till or reduced tillage versus full inversion tillage indicate that the mean C sequestration over a depth greater or equal to 30 cm over a period of about 15 years is negligible on average (Luo et al., 2010a) or small (mean value = 3.4 t C ha^{-1}; Virto et al., 2011). Virto et al. (2011) have shown that the tillage effect is partly attributable to changes in C inputs. Moreover, climatic factors such as annual precipitations can also explain variations in SOC sequestration in no-till soils, as demonstrated by Blanco-Moure et al. (2013) and Dimassi et al. (2014). The latter authors established linear relationships between the rate of change in SOC content and the water balance during the studied period. If we apply these relationships to our conditions with a relative dry climate (mean annual precipitation = 627 mm and water balance = –108 mm), we conclude that the effect of no-tillage *per se* in the CA system may have led to a carbon sequestration rate of 0.17 t C ha^{-1} yr^{-1} between 1998 and 2014 in the layer 0–5 cm, and 0.11 t C ha^{-1} yr^{-1} in the layer 0–30 cm. Therefore, the no-till effect by itself would have contributed 20% to the total sequestration rate (0.55 t C ha^{-1} yr^{-1}). Hence, the change in crop rotation is more likely to explain SOC increase than the no-till practice. Furthermore, the amount of crop residues has been shown to be an essential factor in SOC storage (*e.g.* Luo et al., 2010a, b; Powlson et al., 2011). At “La Cage”, the additional crops introduced in the CA system contributed to increase the total C inputs. The impact of C inputs was also studied by Mary and Justes (2012) and Poeplau and Don (2015) who analyzed long-term studies focusing on catch crops or cover crops. The authors reported mean SOC sequestration rates of 0.29 and 0.32 t C ha^{-1} yr^{-1} respectively during a period comparable to ours (15 and 12 years) when these additional crops were introduced. However, a weak correlation was found at La Cage between changes in SOC stocks and total C inputs (R^2 = 0.38, $p < 0.10$), revealing that SOC stock changes were also due to other factors, such as the type of crop residue depending on species.

Indeed, the effect of crop diversity can also influence SOC storage. Luo et al. (2010b) studied the effect of this practice in a *meta*-analysis focusing on the impact of agricultural practices on SOC changes in Australia over a mean duration of 11-yr. They found that increasing crop diversity (rotation *vs* monoculture) had a small effect on SOC stocks (+5%) but a larger effect (+18%) when perennial legumes were introduced in the rotation. More recent studies underline the relevance of this finding: Tiemann et al. (2015) observed an influence of crop diversity on SOC stocks that was mainly explained by the introduction of a legume cover crop (pure red clover or mixed with rye). In a fescue-alfalfa rotation, Ferchaud et al. (2016) also found an important SOC storage rate of 0.87 ± 0.28 t C ha^{-1} yr^{-1} compared to a rotation of annual crops (sorghum-triticale) during a 6 yr period. Similarly, Alburquerque et al. (2015) found a higher SOC sequestration rate in a alfalfa-maize sequence compared to a winter wheat-soybean rotation

(+0.50 t C ha^{-1} yr^{-1} over 0–100 cm), both systems being in no-tillage for 21 yr. Although it is difficult to disentangle the importance of these practices on SOC storage, some authors managed to study them jointly. Taking the oat-maize rotation as the baseline of their study, Conceição et al. (2013) found higher SOC sequestration in diversified cropping system during 18 years. More precisely, the addition of a legume cover crops (vetch or cowpea) to the cropping system increased the SOC sequestration for tilled and no-tilled systems (+0.28 and +0.34 t C ha^{-1} yr^{-1} respectively). This increase was higher than the effect of an exclusive change to no-tillage in the simple or diversified rotation (+0.18 and +0.25 t C ha^{-1} yr^{-1} respectively).

In our ORG system, we found a significant increase in SOC stock between 1998 and 2014 (+12%), whereas SOC stocks did not vary significantly in the CON and LI systems. This confirms the relevance of long-term studies with a good characterization of all plots at time 0 to detect true differences between treatments (Neto et al., 2010). There are four possible explanations for this increase: i) the lower (although not significantly) initial SOC stock in ORG compared to the other treatments which was therefore more distant from the equilibrium level; ii) the possible C inputs derived from additional weeds, even though weeds were rather well controlled by mechanical operations; iii) the possibly higher C input derived from roots in ORG compared to CON due to enhanced root growth in nutrient limited conditions as shown by Chirinda et al. (2012); iv) the presence of perennial legumes in the crop rotation, as explained above.

One example of the impact of C input on SOC sequestration in organic cropping systems in particular is presented by Pimentel et al. (2005). They measured higher SOC sequestration in an organic crop rotation including a hairy vetch catch crop compared to a conventional rotation (+7% on the 0–30 cm depth), under similar C inputs. Similarly, Reid et al. (2015) found that the root turnover rate of alfalfa was as important as that of perennial ryegrass (3.7 yr^{-1}) which is known to have a high sequestration rate (*e.g.* Soussana et al., 2007). Conversely, after 18 years of experiment comparing organic and conventional systems including alfalfa in the rotation, Bell et al. (2012) found no significant difference in SOC stocks over 0–30 cm. Our results, which suggest that the perennial crop alfalfa had an essential contribution to SOC storage in the ORG system through important root turnover and rhizodeposit inputs, are consistent with Pimentel et al. (2005) and Reid et al. (2015) but not with Bell et al. (2012). The difference with Bell et al. (2012) is most likely explained by the fact that alfalfa was less frequently cut in their study (twice a year) so that the root turnover was lower.

4.3. SOC distribution over the old ploughed layer in CA

The carbon sequestration observed in the CA system was remarkably high in the upper layer (0–10 cm). Several studies under CA also found similar results. For example, Diekow et al. (2005) analyzed the impact of converting conventional systems to conservation agriculture in Brazil. The conversion into a CA system with a legume cover crop (lablab or pigeon pea) resulted in an increase of 12–16 t C ha^{-1} in the 0–17 cm layer after 17 years, compared to a no-till system without permanent cover.

The two *meta*-analyses comparing SOC distribution in soil layers in no-till versus tilled systems show that tillage induced both positive and negative SOC variations in the soil profile: Luo et al. (2010a) found a mean increase of 3.1 t C ha^{-1} in 0–10 cm and a decrease of 3.1 t C ha^{-1} in 10–30 cm; Angers and Eriksen-Hamel (2008) found a relative increase of 30% in 0–10 cm and a decrease of 26% in 10–30 cm. This distribution is attributable to the effect of tillage *per se*. Likewise, we observed an increase in the CA system (compared to CON) in the layer 0–10 cm, but no decrease in the deeper layers, indicating that the additional C inputs in the CA system due to cover crops were responsible for the major part of SOC sequestration. Besides the amount of C inputs, the specific nature of the cover crop is likely to have contributed to this sequestration, particularly with a greater proportion of root material compared to annual crops. In support of this, Constantin et al. (2010) and Poeplau and Don (2015) have shown that the conversion of catch crop or cover crop residues into stable organic matter was highly efficient. Particularly, the greater contribution of roots to C humification compared to aerial residues has been shown in several studies (Balesdent and Balabane, 1996; Johnson et al., 2006; Kätterer et al., 2007). Rasse et al. (2005) calculated that the mean residence time of root-derived C in soils was 2.4 times that of shoot-derived C.

4.4. Simulation of SOC storage

Our objectives for using the simple AMG model were: i) to estimate the carbon inputs derived from belowground parts of cover crops and ii) to test whether the C mineralization rates could differ between systems, particularly the CA system which was no tilled. Modelling allowed us to simulate the effects of no-tillage and of crop residue inputs in the CA system separately. The model was able to correctly simulate SOC evolution in all cropping systems. The quality of fit was slightly improved by optimizing 3 or 6 parameters compared to the default values. The optimization procedure applied to each system individually (simulation S6) gave relative large confidence intervals for the mineralization rates which did not differ significantly from each other. The optimization made with a common mineralization rate (S3) gave an equivalent quality of fit, indicating that the hypothesis of similar mineralization rates between systems, including CA, could explain the observed data. In the literature, the effect of no-till on the long-term on mineralization rates is controversial. For instance, Paustian et al. (2000) compiled the results of three studies calculating the mean residence time of SOC (MRT, inverse of the mineralization rate) in long-term experiments comparing no-till and conventional tillage, using the natural ^{13}C tracing technique. The MRT (average of the three sites) was found to be 1.9 times higher in the no-till systems. However, using the same technique, Haile-Mariam et al. (2008) did not find any difference in MRT between no-till and tilled systems in three other long term experiments in USA. To address this controversy, we tested the results of Paustian et al. (2000) at "La Cage" by assuming that the MRT in CA system was 1.9 times greater than in the other systems. The model thus parameterized overestimated SOC stocks in the CA system starting from 2003 and diverging continuously after (simulation S'0 in Fig. 3). Therefore the hypothesis of a much greater MRT in the CA system was rejected. This conclusion is consistent with results obtained by Oorts et al. (2006, 2007) for carbon and nitrogen both in laboratory and *in situ* and with the review made by Mary et al. (2014) showing small or insignificant differences in nitrogen mineralization rates in long-term experiments only differing in tillage techniques.

5. Conclusion

We quantified SOC stocks and their temporal dynamics over 16 years in the long-term experiment of "La Cage" (northern France) comparing conventional and alternative cropping systems. The SOC stocks did not change throughout time in conventional (CON) and low-input (LI) systems, slightly increased in the organic (ORG) system and increased markedly in the top soil layer (0–10 cm) of the conservation agriculture (CA) system. The amount and nature of C inputs, particularly the additional belowground inputs due to cover crops in the CA system, were able to explain this temporal evolution. Another significant result in the CA system was the constancy of SOC stocks in the layer 10–30 cm compared to the other treatments and also throughout time, contrasting with the SOC decline often found in this layer in no-tilled situations. Modelling SOC stocks evolution was successfully achieved for all of the cropping systems with an optimized common mineralization rate and higher belowground inputs from alfalfa and fescue. Our results stress the importance of long-term studies with initial and dynamic characterization of SOC stocks throughout time which allows a better understanding of the relevant components of farming practices in carbon storage, highlighting the effect of permanent plant cover.

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Appendix A.

Formulae used to calculate aboveground biomass production of cover crops and catch crops.

	Crop and management	Formula	Definition and Parameters	Reference
Eq. (1)	Catch crop and cover crop (apart from alfalfa)	Weibull $DM = a.\left(1 - e^{-b.\sum(T-Tb)^c}\right)$	DM = crop biomass (t ha^{-1}) for oat and fescue: a = 5.84, b = 0.71, c = 2.67 for clover: a = 4.37, b = 0.38, c = 4.42 for fodder radish: a = 6.09, b = 0.59, c = 1.76	Laurent et al., 1995
Eq. (2)	Alfalfa cover crop establishment in early september, and spring and summer regrowth.	$LAI = e^{(a.\sum(T-Tb))-b}$	LAI = leaf area index in autumn a = 0.0025 and b = 5 in spring a = 0.0024 and b = 0 in summer a = 0.0035 and b = 0	Beaudoin and Thiébeau unpublished Justes et al., 2002
Eq. (3)		$PAR = Rg.f$	PAR = photosynthetically active radiation (MJ m^{-2}) Rg = global radiation (MJ m^{-2}) f = photosynthetically active fraction f = 0.48	Varlet-Grancher et al., 1982
Eq. (4)		$PARi = PAR.g.(1 - e^{k.LAI})$	$PARi$ = intercepted PAR (MJ m^{-2}) g = 0.97 and k = 0.88	Gosse et al., 1982, 1984
Eq. (5)		$DM = PARi.RUE$	RUE = radiation use efficiency	
Eq. (6)	Alfalfa cover crop autumn growth	$LAIpot = c.\sum(T - Tb)$	$LAIpot$ = potential LAI c = 0.0092	Coulmier, 1990
Eq. (7)		$\varepsilon ipot = g.(1 - e^{-k.LAIpot})$	$\varepsilon ipot$ = potential interception efficiency	id
Eq. (8)		$PARpot = \varepsilon ipot.PAR$	$PARpot$ = potentially intercepted PAR (MJ m^{-2})	
Eq. (9)		$LAI = -\frac{1}{k}.\log\left(1 - \frac{PARpot-PARsen}{g.PAR}\right)$	$PARsen$ = PAR not intercepted due to senescent leaves $PARsen$ = 0.02	id
Eq. (10)		$\varepsilon i = g.(1 - e^{-k.LAI})$	εi = interception efficiency	id
Eq. (11)		$PARi = \varepsilon i.PAR$		
Eq. (12)		$SEN = j.(LAIpot - LAI)$	SEN = LAI of senescent leaves j = 0.25	id
Eq. (13)		$DM = i.PARi - SEN$	i = 0.015	id
Eq. (14)		$DMm = DM.LERm$	DMm = biomass of the cover crop associated with a cash crop (t ha^{-1}) $LERm$ = land equivalent ratio of the cover crop for alfalfa, fescue and fodder radish: $LERm$ = 0.5 for clover: $LERm$ = 0.65	Szumigalski and Van Acker, 2008; Shili-Touzi, 2009
Eq. (15)	Alfalfa as main crop	$DM = DMref(i)$	i = cutting number $DMref(1)$ = 5.0 $DMref(2)$ = 9.0 $DMref(3)$ = 10.5 $DMref(4)$ = 12.5 $DMref(5)$ = 13.0	

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2016.07.008.

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Article and appendix

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