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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.