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Agricultural practices that store organic carbon in soils: is it only a matter of inputs ?

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Abstract
Agricultural soils have a high C sequestration potential because of their generally low SOC stocks. Here we investigated the effect of alternative cropping systems, conservation agriculture (i.e. no tillage and permanent cover crop) and silvo-arable agroforestry on SOC stocks using long term experiments of 16 and 18 years in France. We measured increased SOC storage in the surface soil layer (0-30 cm) compared to the reference situations. While there was no difference in SOC mineralisation rates, the OC inputs were considerably increased in the alternative cropping systems, due to the associated vegetation (cover crops, trees). This suggests that practices that increase C inputs to soil through additional biomass production would be more effective to store C in soil than practices, such as no-tillage, that are assumed to reduce soil organic matter mineralisation rates.

Keywords: soil, organic carbon, agroforestry, no tillage, conservation agriculture

Introduction

Increasing the world soils carbon stocks by a factor of 4 per mille annually would compensate the global annual CO2 emissions from fossil fuel. This statement, which is the core of the initiative launched by the French government at the COP21, has been translated at the local scale with an aspirational target of an annual 4 per 1000 increase of soil organic carbon (SOC) stocks. Compared to forest and pasture soils, agricultural soils have a higher SOC storage potential, because they are often characterized by low SOC contents(Paustian et al., 2016) and increasing their OC content is associated with benefits in terms of soil properties and ecosystem services. In this context, estimates of the effect of current or innovative cropping practices and systems are particularly needed (Paustian et al., 2016; Stockmann et al., 2013).
Changes in SOC stocks at the plot scale are the result of a balance between input flows - i.e. fresh plant biomass inputs or organic wastes addition into soil-, and output flows which result mainly from mineralisation. The former are potentially increased by cropping practices such as intercropping, cover cropping, planting trees and hedges as well as importing organic wastes. The later are potentially decreased by reduced tillage, which avoids a de-protection of soil organic carbon (Six et al., 2000) (Balesdent et al., 2000). Here, we investigated how alternative cropping practices and systems in annual cropping modified SOC stocks and to which extent it was explained by variations in OC inputs or in losses by mineralisation.

Methodology

We quantified, under temperate conditions, the additional C storage related to the implementation of cropping systems that are recognized to be in the framework of agroecology: conservation agriculture on the one hand and agroforestry on the other hand. These studies were based on long-term experiments (LTE). At La Cage site, in the Paris area, a 16-years old LTE allowed to compare a conservation agriculture system (i.e. no tillage with permanent soil coverage with an associated plant, fescue or alfalfa) to a conventional one on luvisols. At Restinclières LTE in southern France, a 18-year-old silvo-arable agroforestry system associating hybrid walnut trees and durum wheat was compared to a conventional cropping system on fluvisols. The main crops were cereals in both cases. SOC stocks were measured on an equivalent soil mass basis down to 30 cm in the La Cage site (Autret et al., 2016) and down to 1m in the Restinclières site (Cardinael et al., 2015). Organic inputs were quantified at both sites by measuring yields. At La Cage published data were used to estimate belowground crop inputs and crop growth allometric equations to estimate the biomass of the cover crops. At Restinclières, in the agroforestry system, leaf litter, fine root senescence and tree row herbaceous vegetation inputs were measured. Soil sampled 0-30 cm, sieved to 5 or 10 mm, was incubated in the lab to measure SOC mineralisation kinetics The evolution of SOC stocks was modelled at La Cage using a 2 pools model, AMG (Saffih-Hdadi and Mary, 2008) and compared to measured SOC stocks.

Results

Both systems allowed for a net storage of C in soils, which were, for the equivalent of the 0-30 cm tilled layer, of + 0.55 ± 0.16 t ha− 1 yr− 1 for conservation agriculture and of + 0.25 ± 0.03 t ha-1 yr-1 for the agroforestry system compared to the reference conventional system (Table 1). Inputs of OC to soil were increased by about 32% (+1.32 t C ha-1 y-1) in the conservation agriculture system and by 40% (+1.11 t C ha-1 y-1) in the agroforestry system, compared to their respective references (Figure 1). There was no significant differences in the basal respiration (expressed as % of total SOC) between soil in conservation agriculture or agroforestry and their respective references. The model AMG successfully described the evolution of SOC stocks at La Cage LTE and the same mineralization rate of SOC could be used in both the conventional tilled soil and the un-tilled soil in conservation agriculture.

La Cage	Depth	ESM	Conventional		Conservation agriculture	
	(cm)	(t ha-1)	SOC stocks (t C ha-1)			
1998	≈ 0-10	1300	12.8	±1.0	13.4	±2.5
	≈ 0-30	4300	40.4	±3.5	41.9	±8.7
2014	≈ 0-10	1300	13.1	±1.2	21.5	±2.9
	≈ 0-30	4300	41.7	±4.2	51.9	±6.6

	Depth	ESM	Control		Tree row		Inter-row		Agroforestry	
Restinclières	(cm)	(t ha-1)	SOC stocks (t C ha-1)							
2013	≈ 0-8	1000	9.3	±0.1	21.6	±1.0	9.8	±0.4	11.7	±0.3
	≈ 0-28	4000	35.8	±0.2	52.8	±1.4	37.9	±0.6	40.3	±0.5

Table 1. Soil organic carbon stocks in the La Cage and Restinclières long term experiments. Data reprinted from (Autret et al., 2016) (La Cage) and (Cardinael et al., 2015) (Restinclières)

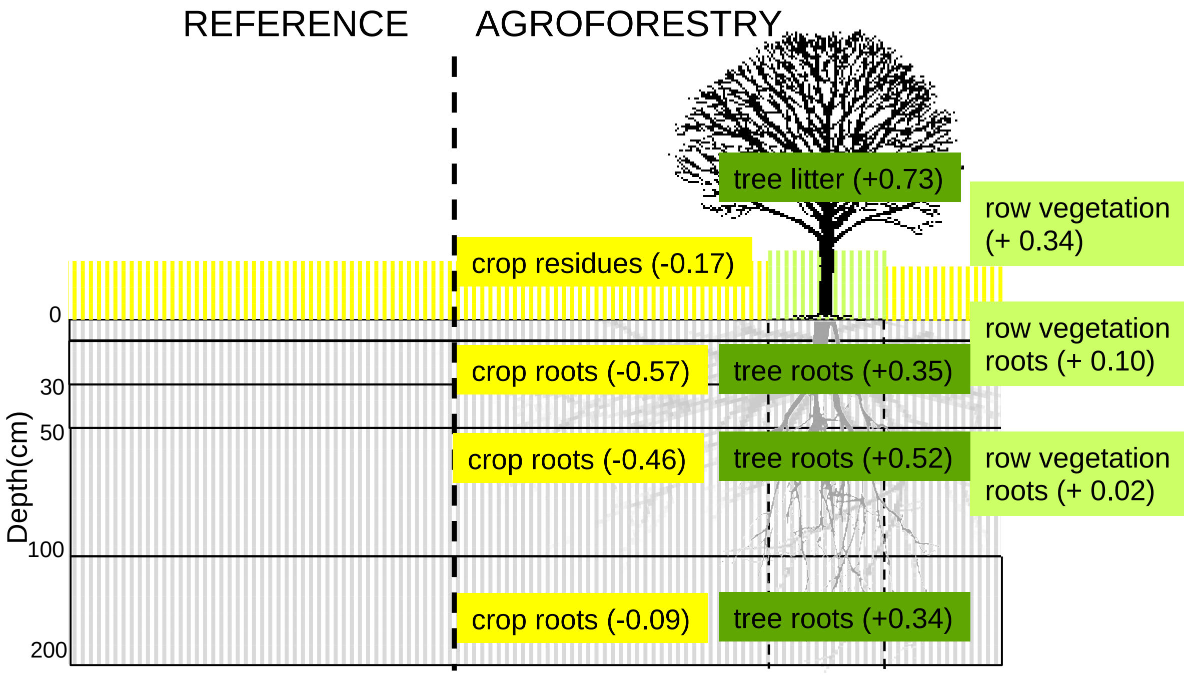

Figure 1. Measured differences in fresh organic carbon inputs from the vegetation to soil in the agroforestry plot at Restinclières, compared to the reference plots. All values are in tC ha-1 y-1 and only average values are presented here.

Discussion

Both alternative cropping systems studied here led to increased SOC stocks, at rates above an annual 4 per 1000 increase. The results are in line with estimates proposed in a recent French national assessment concerning the potential of different agricultural practices to reduce greenhouse gas emissions (Pellerin et al., 2015).

Here, we hypothesised that SOC stocks would increase in the alternative cropping systems because of (i) increased OC inputs due to increased biomass production thanks to the associated vegetation, i.e. cover crops, trees, tree row herbaceous vegetation and (ii) decreased OC outputs due to decreased mineralisation because of no tillage, on the whole surface area of the plot in the conservation agriculture system, or in the tree rows in the agroforestry plot. We found that OC inputs to soil were strongly increased in the alternative cropping system. We did not measure soil respiration in situ, but in vitro measures of SOC mineralisation showed no differences and the modelling exercise suggested that mineralization rates were not affected by the absence of tillage. Thus we did not verify our second hypothesis.

The present results then suggest that increased C inputs to soil through additional biomass production would be more effective to store C in soil than practices, such as no tillage, that are assumed to reduce soil organic matter mineralisation rates. This was also suggested by the (Pellerin et al., 2015) study, in which cover crops between cash crops, hedges, agroforestry, cover crops in vineyards and orchards or buffer grass strips were found, based on a literature review for French pedoclimatic conditions, to store more carbon than no tillage or superficial tillage practices.

Indeed, while no tillage has been one of the most important agricultural practices sought to increase SOC, its effect on SOC stocks has been scaled down in the last years, especially based on meta-analyses (Angers and Eriksen-Hamel, 2008; Luo et al., 2010; Virto et al., 2012). These showed that relative increases in SOC stocks under no tillage are often restricted to superficial soil layers and are extremely variable across soil types and climates. Further (Virto et al., 2012) found that that crop C inputs

differences was the only factor significantly and positively related to SOC stock differences between no tillage and inversion tillage, explaining 30% of their variability.
This questions our understanding of the effect of no tillage on soil organic matter dynamics. In the absence of tillage, more organic matter has been shown to be physically protected from biodegradation, because of a more aggregated soil and a less frequent disruption of the aggregates (Six et al., 2000). In addition, under temperate conditions as here, moister and cooler conditions in no till soils should also decrease mineralization rates (Balesdent et al., 2000). However, less residue incorporation in the absence of tillage could also lead to less physical protection and less SOC stabilization in subsoil layers (Gregorich et al., 2009). A better mechanistic understanding of the complex effects of no tillage on soil organic matter dynamics is needed to reconcile process oriented studies with field scale monitoring of SOC stocks.

Conclusion

One major outcome of the study is that it suggests that to increase soil organic carbon stocks it is probably more effective to increase carbon inputs into the soil than to attempt to reduce outputs. All the practices increasing primary production can be mobilised here: planting of ligneous plants in combination (hedges, agroforestry), replacing bare soil with plant cover, either in space (intercropping) or time (cover crops).

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