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Carbon soil stock change in an intensive crop field near Paris reveals significant carbon losses

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Abstract. Soil is a large pool of carbon (C) storing globally twice and three times more carbon than the atmosphere and vegetation, respectively. Soil organic carbon (SOC) stocks are significantly impacted by land use changes, either negatively when forest or grasslands are turned into crops or positively when the opposite is done. This idea has led to the 4per1000 initiative to increase carbon storage in soils. However, intensive cropping and climate change may lead to organic and inorganic carbon losses from soils, which calls for long-term observations of soil organic carbon stocks in reference ecosystems over the globe. This idea is behind developing a reference soil sampling protocol for all EU Integrated Carbon Observing System research infrastructure (ICOS) ecosystem sites. We present the first case study of SOC stock measurements with the ICOS protocol at the French crop site FR-Gri in 2019 and compute the soil stock evolution from 2005 to 2019 for a wheat-maize-barley-oilseed-rape crop rotation. A significant decompaction of the 0-15 cm soil layer was observed over the 15 years, with a 25% decrease in bulk density in the 0-5 cm layer and a 10% decrease in the 5-15 cm layer, which can be attributed to reduced tillage performed since 2004. A significant increase of organic carbon content was observed in the same soil layers, around 15% in the 5-15 cm layer and 20% in the 0-5 cm layer. Despite its higher SOC content, the carbon stock decreased significantly in the 0-5, 5-30 and 0-60 cm layers because of the decreased bulk density. Overall, the SOC stock decreased by around 960 g C m^{-2} over the 13.25 years in the 0-60 cm layer, which corresponds to a decrease rate of 72 ± 17 g C m^{-2} yr^{-1} as estimated with a fixed depth approach. The equivalent soil mass approach led to a very similar estimate of 70 ± 16 g C m^{-2} yr^{-1}. Overall, an organic carbon loss of 0.6% year^{-1} was observed, consistent with previous studies. We utilised the soil carbon cycling model AMG to simulate the soil carbon dynamics over the period and beyond. Based on recorded exports and imports and estimated residue return to soil, the model was in perfect agreement with the soil stock measurements. The AMG model simulation was also consistent with the carbon flux balance reported between 2006 and 2010 as reported by Loubet et al. (2011), and predicted a stabilisation of the soil stock around 2028 with an overall decrease of 15% of the soil organic carbon stock compared to 2005. This observed destocking may be explained by a shift towards larger exportations and lower residue return at this site compared to previous practices. This result questions the feasibility of the 4per1000

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aspirational target and stresses for high-quality soil SOC evolution measurements as developed by the ICOS research infrastructure to answer this question.

1 Introduction

Soil is a significant carbon (C) and nitrogen (N) biogeochemical cycle pool. According to the latest estimations, soils store 1500 to 2400 Gt C globally to a depth of 1 m as organic matter (Batjes, 1996; Sanderman et al., 2017) and almost the same amount as inorganic C to a depth of 2 m (Zamanian et al., 2021). Soils contain approximately two times more organic C than the atmosphere and vegetation (Antón et al., 2021). Hence, minor changes in this large soil reservoir could affect future atmospheric carbon dioxide (CO_2) concentrations (Minasny et al., 2017). Soil organic carbon (SOC) stocks are significantly impacted by land use through crop and forest management. It is estimated that soils have globally lost 140 to 150 Gt of organic carbon due to land use intensification since the onset of agriculture 8000 to 120000 years ago (Schimel, 1995). Likewise, increased N deposition and intensification of N use in agriculture since the 20^{th} century have also affected soil inorganic carbon (SIC) stocks reducing it through carbonate weathering. This process together with global warming could counteract efforts to increase SOC by changing land management (Raza et al., 2020; Song et al., 2022; Zamanian et al., 2021; Schrumpf et al., 2011). ~~S~~pecific agricultural practices, like persistent vegetative cover or high organic inputs are promoted to partially restore SOC and mitigate climate change (Lal, 2004; Poeplau and Don, 2015). On the contrary, intensive farming based on monoculture performed throughout the 20^{th} century is expected to aggravate climate change (Autret et al., 2016). Minimum and no-tillage was also promoted to restore SOC since the 2000s, but growing evidence shows that this may not be the case (Chenu et al., 2019). It is however evaluated that 2 to 3 Pg C yr-^{1} could be sequestered in the first metre of agricultural soils by changing the land uses and agricultural practices to more conservative agriculture. These practices if generalised may offset about a third of the global anthropogenic greenhouse gas emissions as estimated in 2016(Minasny et al., 2017). However, these estimations may be over-optimistic as the potential for carbon storage diminishes with time after land conversion, as soil reaches a new equilibrium (Minasny et al., 2017; Baveye et al., 2018). Moreover, the large land surface required for conversion to permanent forests and grassland that are recognised as the best practices to restore carbon may threaten the food supply worldwide.

Overall, nowadays, European croplands are considered a net carbon source to the atmosphere of 10 ± 9 g C m^{-2} yr^{-1}, while grasslands and forests are net atmospheric sinks of 57 ± 34 g m^{-2} yr^{-1} and 20 ± 12 g m^{-2} yr^{-1} (Schrumpf et al., 2011; Schulze et al., 2009). A recent review of bottom-up estimates and national inventories in Europe finds that ecosystems are an overall sink of ~100 Tg C yr^{-1} , an estimate that is characterised by large uncertainties of ± 360 Tg C yr^{-1} (Petrescu et al., 2021). The same review shows that top-down estimates are affected by an even higher uncertainty, too large to allow for the verification of national inventories. Therefore, accurately determining SOC stocks and their changes with time is essential to verify the actual carbon fluxes to ecosystems and monitor their evolution over time (Poeplau et al., 2017).

The measurements of SOC stocks are subject to uncertainties, and it is challenging to detect and accurately quantify their changes reliably. Indeed, measuring SOC stocks needs quantification of both the mass and the organic carbon (OC) content of the soil fine earth fraction (sieved at 2 mm) in the different soil layers (Molteni and Corti, 1998). These quantities are highly variable spatially and require dense sampling in order to diminish the uncertainty and be able to detect SOC changes over time (Batjes, 1996). Moreover, the rock fraction (RF), evaluated as the coarse

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mineral fragments larger than 2 mm, is assumed to be free of organic matter, which is only partially accurate (Corti et al., 1998).

Measuring soil fine earth fraction is based on bulk density (BD) and RF measurements, which are time-consuming. Bulk density is often estimated by pedo-transfer functions (PTF), which are known to give random errors (Knotters et al., 2022b; Harbo et al., 2022; Schrumpf et al., 2011). In some studies, the choices of PTF equations and parameters and the overlooking of RF lead to systematic uncertainties in SOC stock estimates, among which RF is the most critical (Poeplau et al., 2017; Beem-Miller et al., 2016; Wiesmeier et al., 2012; Ipcc, 2003).

Change in BD over time needs to be considered when looking into SOC changes over the decades. Indeed, swelling and shrinkage in clayey soils linked with climate change and seasonality, or compaction and decompaction linked to agricultural practices and water content, as well as erosion, may all change BD (Hopkins et al., 2009). To address this issue, Ellert and Bettany (1995) proposed the equivalent soil mass (ESM) method instead of the fixed depth (FD) method to measure SOC stock changes. In the FD method, SOC stock changes over time are evaluated at constant soil depths and can induce significant biases due to the variation in BD (Beem-Miller et al., 2016). In the ESM approach, SOC stocks are evaluated for a constant soil mass per unit area, and possible BD changes are compensated by varying the sampling depth (Von Haden et al., 2020; Ellert and Bettany, 1995; Wuest, 2009; Vandenbygaart and Angers, 2006). Differences between FD and ESM can overwhelm variations caused by tillage and crop residue removal rates in the range of 10% of SOC changes (Xiao et al., 2020; Du et al., 2017). Comparing SOC stocks on the same soil mass per unit area was recognised as a better practice than the fixed depth approach (Von Haden et al., 2020; Xiao et al., 2020; Autret et al., 2016; Bollmann et al., 2013; Schrumpf et al., 2011) and recently recommended as the reference method by FAO and IPCC (Fao, 2019; Smith et al., 2020; Ipcc, 2019).

Soil organic carbon stocks are key evaluations that are included in the ICOS (Integrated Carbon Observation System) European Research Infrastructure Consortium (Heiskanen et al., 2022), which contained 50 high quality and standardised ecosystem sites (Class1 and 2 stations) in 2024, covering the diversity of European soils and ecosystems. At each site, the SOC stock is measured when the site enters ICOS and from 5 to 10 years later to evaluate the SOC stock change over time. This change can be then compared to the integrated carbon fluxes at the site boundaries over that period, which comprise the net ecosystem productivity, imports and exports from the site as well as lixiviated fluxes (Ceschia et al., 2010; Loubet et al., 2011; Aubinet et al., 2009). Monitoring SOC stocks requires an adequate sampling strategy (Arrouays et al., 2012; Schrumpf et al., 2011; Saby et al., 2008; Don et al., 2007). Design-based sampling strategies, based on randomly chosen sampling points, provide model-free and unbiased mean and standard deviation estimates. On the contrary, a statistical model is chosen in a model-based approach and sampling points can then be chosen subjectively (Brus and Degruijter, 1997; Laslett et al., 1997; Jaap J. et al., 2006). In ICOS, a designed-based approach was selected as a way to provide unbiased and robust estimates with a limited number of samples (Loustau et al., 2017; Arrouays et al., 2018). Soils started to be sampled in ICOS in 2017, and about a third of the sites have been sampled. Given a 10 years turnover time, the first SOC stock change evaluations at these sites with the ICOS methodology will only be available from 2027 onward. However, 12 ICOS sites were sampled from 2005 to 2010 using a systematic sampling grid approach within the EU CarboEurope project, as reported by Schrumpf et al (2011). It is therefore tempting to evaluate whether these previous sampling could be used to calculate soil stock changes at these sites over the last 15 years.

The main objectives of this study are to (1) evaluate the SOC stock change between 2005 and 2019 at the ICOS crop site FR-Gri, (2) compare the equivalent soil mass and fixed depth SOC stock changes calculations, (3) discuss

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the uncertainties in these estimations, and (4) compare it to the soil carbon cycle model AMG prediction (Clivot et al., 2019) and to previously established carbon flux balance estimations at the same site by Loubet et al. (2011).

2 Material and methods

2.1 Study site

The study site is the ICOS FR-Gri ecosystem site, a crop field of 19 ha located 40 km west of Paris, in northern France (48. 9 N, 1.95 E, elevation 125 m) (**Figure 1**). During the studied years (between 2005 and 2019), the mean annual air temperature and rainfall were 11.2 °C and 586 mm, respectively. The site has a gentle slope towards the north, with an average slope of approximately 1%. Agricultural fields mostly surround the south and west of the study area. The soil is a Luvisol on the south-east and a decarbonated Hypereutric Cambisol on the north west (Wrb, 2014). The surface soil is a silt loam (71.3% silt and 18.9% clay in the top 15 cm), with a variable soil depth from more than 1 m on the southeast to around 0.6 m on the northwest. The average pH was 7.6, and average bulk density 1.3 g cm^{-3}, and the $CaCO_3$ content was 3% and 20% on average in the 0-50 cm and 50-100 cm, respectively (**Table S1**). The OC content in the surface layers was around 20 g C kg$^{-1,}$ as reported in 2011 (Loubet et al., 2011).

Figure 1. (left) The ICOS station network. (right) FR-Gri 19 ha field site highlighted in yellow. The CO_2 flux mast is shown in red. The farm is mixed farm with cows and sheep in the buildings visible on the south of the site. The site was cultivated for over 100 years, with no clear record of when cultivation started. It was highly fertilised in the 1980s with sewage sludge. On the left, the image is taken from the ICOS web site © ICOS RI. On the right the image was taken from the French GeoPortal © IGN 2023. The image was taken in 2021.

The dominant crops in the crop rotation are winter wheat, silage maize (preceded by a mustard catch crop), and winter barley, with two years of oilseed rape during the period (**Table 1**). These crops are herbaceous mixing C3 (wheat, barley, triticale, oilseed rape, mustard) and C4 (maize) plants. The crop production is mainly exported as grain or silage (maize), but residues are also exported for animals and bioenergy. The average carbon export was 470 ± 54 g C m^{-2} yr^{-1} (**Table 1**). The field received some slurry and manure regularly, with an average carbon input of 114 ± 13 g C m^{-2} yr^{-1}. The average above ground biomass crop residues left on the field were evaluated using the exported biomass and allometric coefficients (Clivot et al., 2019; Clivot et al., 2023). They represent 151 ± 17 g C m^{-2} yr^{-1} , around 1/3 of the exported carbon, a slightly higher than the imported one. The biomass of mustard was not measured but taken equal to the mean estimated biomass of mustard in France (Soleilhavoup and Crisan, 2021).

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2.2 Carbon flux balance estimations using the ICOS approach between 2006 and 2010

The carbon flux balance was estimated from 2006 to 2010 in Loubet et al. (2011), based on the Eddy Covariance (EC) micrometeorological method. In brief, the carbon flux balance of the field or net biome productivity (NBP) was computed as $NBP = NEE + F_{orga.fert} + F_{seeds} - F_{leach} - F_{harvest}$, where NEE is the CO_2 flux above the crop integrated over time called net ecosystem exchange, $F_{orga.fert}$ is the carbon input through organic fertilisation, F_{seeds} is the carbon input through seedling, F_{leach} is the organic and inorganic carbon losses by lixiviation, and $F_{harvest}$ is the export of carbon through harvest. See Loubet et al. (2011) for details.

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Table 1. Crop rotation, yield, exports and imports, and nitrogen (N) applied over the 15 years between the two sampling campaigns at the FR-Gri site. Carbon export was evaluated based on the farmer's record of grain, straw and silage exports. The aerial crop residue return was evaluated based on the exports and the allometric coefficient of the AMG model, as explained in the manuscript. A 0.44 g C g-1 dry biomass carbon content was assumed to compute the exports and imports. Organic nitrogen was mainly cow slurry and, on a few occasions, manure. Mineral fertilisation was mainly urea ammonium nitrate.

crop	year	part of the plant harvested	Exported Carbon (g C m^{-2})	Imported Carbon (g C m^{-2})	aerial crop residues returned to soil (g C m^{-2})	Organic Nitrogen applied (kg N ha^{-1})	Mineral Nitrogen applied (kg N ha^{-1})	Total Nitrogen applied (kg N ha^{-1})
mustard	2005	None			90 ± 10			
maize	2005	above 20 cm -	330 ± 40		10 ± 0		140 ± 10	140 ± 10
wheat	2006	seed and straw	640 ± 70		170 ± 20		110 ± 10	110 ± 10
barley	2007	seed and straw	440 ± 50		150 ± 20		110 ± 10	110 ± 10
mustard	2008	None			90 ± 10			
maize	2008	above 20 cm -	550 ± 60	120 ± 20	20 ± 0	80 ± 10	60 ± 0	130 ± 10
wheat	2009	seed, straw and chaff	640 ± 70	140 ± 20	150 ± 10	80 ± 10	170 ± 10	250 ± 20
Triticale	2010	seed, straw and chaff	490 ± 60	240 ± 40	90 ± 10	220 ± 40	100 ± 10	320 ± 40
maize	2011	above 20 cm -	610 ± 70	120 ± 20	20 ± 0	80 ± 10		80 ± 10
wheat	2012	seed, straw and chaff	640 ± 70	160 ± 30	100 ± 10	170 ± 30	70 ± 0	240 ± 30
rapeseed	2013	seed and chaff	240 ± 30		370 ± 40		110 ± 10	110 ± 10
wheat	2014	seed and straw	420 ± 50	180 ± 30	110 ± 10	130 ± 20	110 ± 10	240 ± 20
mustard	2015	None			90 ± 10			
maize	2015	above 20 cm -	430 ± 50	280 ± 50	20 ± 0	290 ± 50		290 ± 50
wheat	2016	seed, straw and chaff	440 ± 50	50 ± 10	190 ± 20	90 ± 20	220 ± 10	310 ± 20
rapeseed	2017	seed	170 ± 20		440 ± 40	0 ± 0	120 ± 10	120 ± 10
wheat	2018	seed and straw	450 ± 50	300 ± 50	130 ± 10	190 ± 30	80 ± 0	270 ± 30
mix intercrop	2019	All plants for silage	50 ± 10				40 ± 0	40 ± 0
maize	2019	above 20 cm -	540 ± 60	120 ± 20	20 ± 0	80 ± 10		150 ± 10
		average (g C m^{-2} y^{-1} or kg N ha^{-1})	470 ± 54	114 ± 13	151 ± 17	93 ± 11	100 ± 11	193 ± 22

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2.3 Soil sampling schemes

Two different sampling strategies were used during two campaigns in 2005 and 2019 (**Figure 2**). In the 2005 campaign, 100 soil samples were taken following a systematic design corresponding to a regular grid (7 × 7 m), and samples were collected using both 8.3 and 8.7 cm inner diameter corers in December 2005 during winter wheat dormancy. Soil cores were divided into seven layers (0-5, 5-10, 10-20, 20-30, 30-40, 40-50, and 50-60 cm). The 2005 campaign results were reported in Schrumpf et al. (2011). In the 2019 campaign, 99 soil samples were collected in March, following the ICOS protocol (Arrouays et al., 2018), which consists of a stratified simple random sampling design. One sample between 60 and 100 cm was not reachable due to rock density. The field was at that time covered with a mix of CIPAN crops (oats, field bean, pea, clover, and flax). The studied area was divided into 10 geographically compact equal-area strata (Walvoort et al., 2010). Within each stratum, two primary sample locations were randomly selected (simple random) for a total of 20 primary locations (SP-I). At each primary location, five secondary locations (SP-II) were randomly selected within a buffer area of 10 metres, where the soil was sampled using a 5.5 cm inner diameter corer. Each core was separated into sub-samples at 0-5, 5-15, 15-30, 30-60 and 60-100 cm depth. Finally, cores were mixed to form a composite sample at each primary location and each layer.

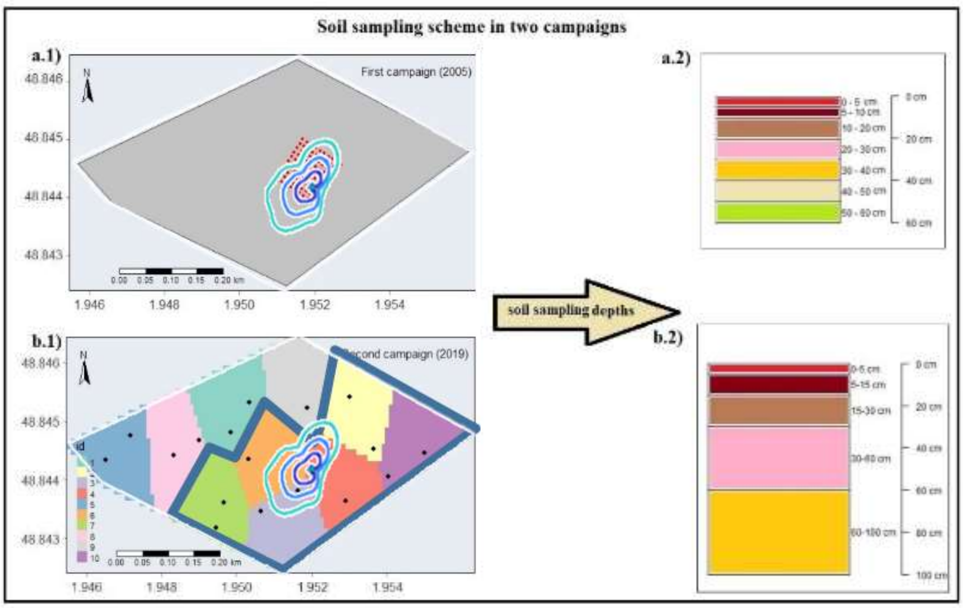

Figure 2. a. The sampling points and depths used in the 2005 campaign. The grey area represents the FR-Gri field. b. In 2019 the location of the aggregated SP-I samples in the 10 strata are shown. The bold blue line on the 2019 campaign shows the reduced sampling area used for comparison with the 2005 campaign. The blue lines show the 50, 70 and 80% footprint from the Eddy covariance mast.

The two campaigns were carried out on different areas around the eddy covariance system: the 2005 campaign focused on an area representative of the eddy-covariance mast maximum footprint, while 2019 encompassed the whole 19 ha field. The footprint determined using Kljun et al. (2015; 2004), was well inside the 19ha field except for some stable nights when it reached the surroundings. Four strata of the 2019 campaign intersect the 2005 area. To evaluate the uncertainty linked with the spatial variability in SOC stock, the 2019 data were either including

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all the strata (referred to as *the whole field*) or only the strata having soil characteristics similar to the 2005 sampling area (strata 2, 3, 4, 6, 7, 9, 10, referred to as *reduced area*). The surface soil was similar in 2005 and 2019, with sampling occurring after soil surface preparation, before and after maize sowing.

2.4 Soil samples preparation and analyses

In the 2005 campaign, all soil samples were preserved at 4°C before processing. Rock fraction (>4 mm) and root fraction (>1 mm) were separated from the samples before drying at 40°C. The rock and root fractions were separately air-dried, and the remaining samples were sieved to <2 mm. The particles >2 mm were mixed with the rock fraction, and then the dry weights of the combined roots and rock fractions were measured (Schrumpf et al., 2011). In the 2019 campaign, samples were air-dried at around 30°C and then sieved to separate the fine earth (sieved at 2 mm), rock and root fractions before laboratory analysis. The root and rock fractions were oven-dried at 70°C and 105°C, respectively, before weighing. In both campaigns, OC content was determined in the sieved fine earth sample by dry combustion (ISO 10694), which measures the total carbon content in the soil. Overall in 2005 and 2019, the soil preparation and analysis were therefore very similar. Carbonate was measured by acidification with a hydrochloric acid (HCl) solution and the analysis of the released carbon dioxide (CO_2), which is converted into $CaCO_3$ (g kg^{-1}). When the sample contains carbonates (700 g kg^{-1} > $CaCO_3$ > 1 g kg^{-1}), the mineral carbon content was calculated as C = 0.12 x $CaCO_3$. The organic carbon content was then computed as the total carbon content minus the mineral carbon content. When the $CaCO_3$ content was larger than 700 g kg^{-1}, to avoid a deterioration in the accuracy of organic carbon deduced from total carbon, samples were first treated with HCl to eliminate carbonates and then total carbon determined as explain previously.

2.5 SOC stock calculation

The stock of organic carbon SOC_{stock}^{60cm} (g C m^{-2}) in the 60 cm layer was calculated as:

$$SOC_{stock}^{60\,cm} = \sum_{\mathrm{i=1}}^{\mathrm{n}} \frac{m_{fe_i}}{m_{soil_i}} \times \mathrm{BD_i} \times \Delta\mathrm{z_i} \times SOC_{fe_i} \times 10 \tag{1}$$

Where n is the number of layers in which the soil core was divided down to 60 cm, i is the layer index. m_{fe} (g) is the mass of fine earth, and m_{soil} (g) is the total soil mass (including rocks and roots), BD (g cm^{-3}) is the bulk density, Δz is the layer thickness (cm), and SOC_{fe} (g C kg^{-1}) is the soil organic carbon content in the fine earth fraction of the layer. The factor 10 arise for the change in units from g to kg of soil and cm^2 to m^2. The bulk density is defined as the ratio of m_{soil} to the soil volume in that layer and is computed as:

$$BD_i = \frac{m_{soil_i}}{S_i \times \Delta z_i} = \frac{m_{soil_i}}{V_{sample_i}} \tag{2}$$

where S is the sampled surface and V_{sample_i} is the sampled volume. Equations (1) and (2) correspond to equation (1) and (2) in Schrumpf et al. (2011) and where used to compute the stocks for the 2005 samples. We note that when combining the equations (1) and (2), the mass of soil m_{soil} and the layer thickness Δz both disappear. In the ICOS stock calculation protocol, the bulk density is therefore not used anymore. The SOC stocks are computed based on the surface sampled S and the mass of fine earth m_{fe} only:

$$SOC_{stock}^{60\,cm} = \sum_{\mathrm{i=1}}^{\mathrm{n}} \frac{m_{fe_i}}{S_i} \times SOC_{fe_i} \times 10 \tag{3}$$

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In equation (3), a term can be identified as the fine soil stock in each layer FSS_i which gives the fine soil stock over the 0-60 cm profile :

$$FSS_{60cm} = \sum_{i=1}^{n} \frac{m_{fe_i}}{S_i} \times 10 = \sum_{i=1}^{n} FSS_i \quad (4)$$

We note here that these equations are adapted for core sampling. When sampling soils with pits, some corrections need to be introduced in equations (1-3) to account for large stones and large roots in the pit. The inorganic carbon stock $SIC_{stock}^{60\ cm}$ was computed in a similar way as the organic carbon stock but replacing the organic carbon content in the fine earth fraction SOC_{fe} by the inorganic carbon content SIC_{fe}.

2.6 Computing the change in SOC stocks

To estimate SOC stocks evolution change, one needs to consider changes in SOC content of the soil (SOC_{fe}) but also possible changes in soil density due to compaction or decompaction that may change the fine soil stock, but also soil erosion (by rain or wind) that may export some soil out of the field. Erosion is negligible at the FR-Gri site due to a slight slope and systematic winter inter-cropping. Decompaction may have happened since the site was converted to reduced tillage from 2000 onwards (Loubet et al., 2011). To consider possible changes in soil bulk density, the SOC stock evolution was estimated with two methods: the fixed depth method (FD), where the stock is summed up over each layer to the same depth for each campaign, and the equivalent soil mass method (ESM) where the SOC stock is integrated down to a varying depth corresponding to a reference soil mass that is set equal for each campaign (Wendt and Hauser, 2013; Ellert and Bettany, 1995; Lee et al., 2009). This latter method also has the advantage of accounting for a common sampling bias with hydraulic corer, which is soil compaction. The fine soil stock in the 0-60 cm layer (eq. 4) varied from 852 to 967 kg m^{-2} in 2005, while in 2019, the fine soil stock in the same layer ranged from 831 and 953 kg m^{-2} (**Table S2**). The reference fine soil stock FSS_{ref} used to compute the equivalent soil mass carbon content in the two campaigns was hence taken to be the minimum in 2005, i.e. 852 kg m^{-2}.

The ESM method was applied by first estimating the mass difference between the mass at 60 cm FSS_{60cm}in each sampling profile and the reference soil mass FSS_{ref}: $(FSS_{60cm} - FSS_{ref})$. The layer depth corresponding to this additional or missing soil mass is then calculated as the ratio of $(FSS_{60cm} - FSS_{ref})$ to the fine soil stock at 60 cm FSS_{60cm}. The SOC stock corresponding to this additional layer (SOC_{stock}^{*}) was then calculated as in equation (1) for the 2005 data:

$$SOC_{stock}^{*} = SOC_{stock_{60cm}} \times \frac{FSS_{60cm} - FSS_{ref}}{FSS_{layer}} \quad (5)$$

Where $SOC_{stock_{60cm}}$ is the soil organic carbon stock, and FSS_{layer} the fine soil stock in the layer just above 60 cm (30-60 cm in 2019 or 50-60 cm in 2005), or in the layer just below 60 cm (60-100 cm layer in 2019), depending on the sign of $(FSS_{60cm} - FSS_{ref})$.

The equivalent soil mass SOC stock was then computed as the sum of the stock to 60 cm plus the additional stock to the reference depth:

$$SOC_{stock}^{ESM} = SOC_{stock}^{60cm} + SOC_{stock}^{*} \quad (6)$$

Note that in this expression, SOC_{stock}^{*} can be positive or negative. However, since the reference mass was the minimum soil mass in 2005, for 2005, SOC_{stock}^{*} was always negative. The difference in soil stock between 2019 and 2005 was calculated for both SOC_{stock}^{ESM} and SOC_{stock}^{60cm}.

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2.7 Statistical inference for assessment of the carbon stock change

Unequal variance t-tests were applied to assess significant differences between the two campaigns' means of SOC stocks estimated by FD and ESM approaches. The *t* value was calculated as:

$$t = \frac{(\widehat{Stock}_{2005} - \widehat{Stock}_{2019})}{\sqrt{\hat{\mathrm{V}}(\widehat{Stock}_{2005}) + \hat{\mathrm{V}}(\widehat{Stock}_{2019})}} \quad (7)$$

Where $\widehat{Stock}$ is the estimated mean stock, $\hat{V}(\widehat{Stock})$ is the estimated sampling variance of the estimated mean stock, and indexes stand for the campaign years.

A design-based approach was used to estimate the means and sampling variances (Jaap J. et al., 2006). The sampling variances of the two campaigns were estimated separately and considered unequal. For systematic random sampling (2005 campaign), the mean estimate is simple, but there is no unbiased estimate of the sampling variance. We implemented the approximation suggested by Brus and Saby (Brus and Saby, 2016), where the systematic random sample is treated as a stratified simple random sample. In the 2019 campaign, a stratified random sampling with equal area strata was used.

In a stratified random sampling with equal area strata and the same number of sites per stratum, the mean and the sampling variance are estimated as:

$$\widehat{Stock} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} Stock_{\mathrm{i}} \quad (8)$$

$$\hat{\mathrm{V}}\left(\widehat{Stock}\right) = \sum_{\mathrm{h}=1}^{\mathrm{H}} w_h^2 \hat{\mathrm{V}}\left(\widehat{Stock}_h\right) = \frac{1}{4} \sum_{\mathrm{h}=1}^{\mathrm{H}} \hat{\mathrm{V}}\left(\widehat{Stock}_h\right) \quad (9)$$

Where $Stock_i$ is the stock at location *i*, *N* is the total number of samples over all strata, $\hat{V}\left(\widehat{Stock}_h\right)$ is the sampling variance of stratum *h*, $w_h^2 = \frac{1}{2}$ is the weight of stratum *h*, and H is the number of strata. The 95% confidence interval is given by:

$$\widehat{Stock}^{95\,CI} = \pm\, t_{2.5}^{N-H} \sqrt{\hat{\mathrm{V}}(\widehat{Stock}_h)} \quad (10)$$

Where $t_{2.5}^{N-H}$ is the 2.5 quantile of a *t* distribution where $(N - H)$ approximates the degrees of freedom.

In 2005, the sampling units were clustered by 2 based on their spatial coordinates into H = n/2 clusters (*n* = 100) using a *k*-means algorithm (Brus and Saby, 2016). The 2 sampling units of a cluster were treated as a simple random sample from a stratum, and the variance was estimated with eq. (8) with H = 50, . The weights were computed by $w_h^2 = n_h/n$, where $n_h = 2$ is the number of units per cluster. The 95% confidence interval was estimated with eq. (9) with a degree of freedom $N - H = 100 - 50 = 50$. In 2019, when the whole field was considered there was H = 10 strata of 2 units each leading to a total number of sampling points N = 20 (called SP-I in ICOS), leading to $N - H = 10$. When part of the field was considered, both the number of samples and H diminished leading to $N - H < 10$

In 2005 and 2019, equations (7-9) where used to compute the carbon stock statistics for each sampling depth available and over aggregated layers 0-15 cm, 15-30 cm and 30-60 cm. In 2019 the layer 60-100 cm was also available.

Simulation of carbon stock evolution with the AMG model

To compare with the measured organic carbon stock evolution in the surface soil (0-30 cm), we computed the carbon stock evolution using the agricultural soil carbon model AMG (Clivot et al., 2019). AMG is a simple soil

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carbon model, considering three organic C pools: (1) a pool including organic C inputs from crop residues, roots and exogenous organic matter (EOM), (2) an active organic C pool, and (3) a stable organic C pool. A proportion (h_a) of C input is allocated to the active C pool, while the remaining proportion ($1 - h_a$) is mineralized. The active C pool decomposes according to first-order kinetics with a rate constant k. k depends on climate (annual temperature, precipitation, potential evapotranspiration) and soil properties (clay, carbonate, pH, C:N ratio). The stable C pool does not decompose and is not supplied by C inputs. The model considers the following C inputs: the aboveground crop residues and imported carbon from manure and slurry (**Table 1**), and the belowground crop residues, computed with allometric coefficient based on the aboveground biomass exportations (Clivot et al., 2023; Clivot et al., 2019). The SOC stock evolution was simulated in the surface layer (0 – 30 cm) for the period 2005-2019 on a yearly time base. The SOC stock was initialized based on the 2005 measurement campaign to 8.4 kg C m^{-2} in 2005. The proportion of active C was set to 65%, as Clivot et al. (2019) proposed for agricultural fields with a long-term history of cultivation.

3 Results

3.1 Summary statistics of the measured soil properties in both campaigns

The 2005 campaign was already published by Schrumpf et al. (2011), but the 2019 campaign has yet to be published. This campaign sampled an area much larger than the 2005 campaign, which covers a fraction of the field with shallower soil, as Loubet et al. (2011) pointed out and as is visible in **Figure 3.** It shows a more significant rock and inorganic carbon (carbonates) fraction in the shallow layers on the northeast side of the field. The area sampled in 2005 (**Figure 2**) showed a rock fraction smaller than a few per cent, also reported by Schrumpf et al. (2011). One sampling below 60 cm was impossible on the northwest part of the field due to very stony soil, leading to one missing data points in the 2019 .

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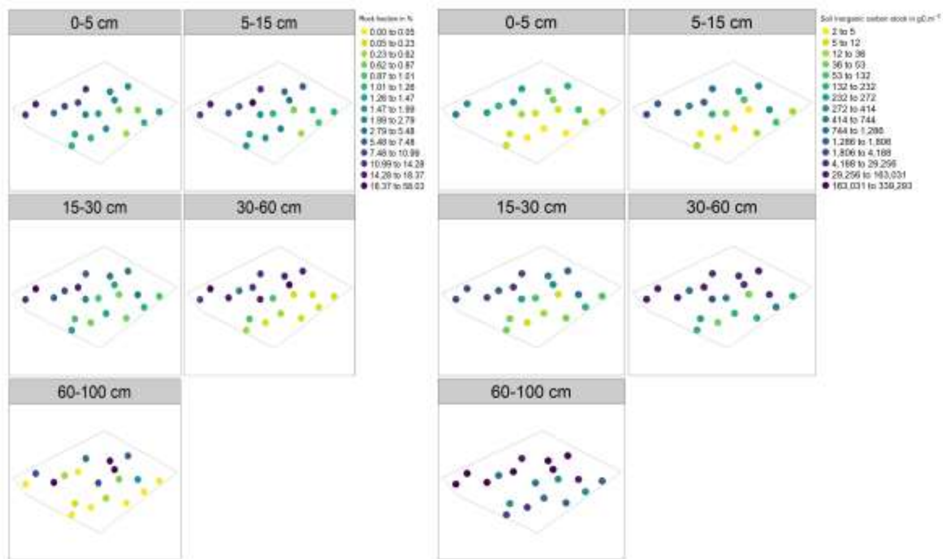

Figure 3. Rock fraction (left) and carbonates (right) spatial variability was measured in 2019 at the 20 spatial sampling points at several layers. In the 60-100 cm layer the SP-15 is missing as it was too stony to sample.

For the whole soil profiles, the density distribution of soil bulk density (BD) ranged from 0.75 to 1.8 g cm^{-3}, with a primary peak around 1.5 g cm^{-3} and a secondary peak around 1.1 g cm^{-3} that appeared in the 2019 campaign in the reduced area, showing an overall decrease of the bulk density with time at the surface (**Figure 4**). This decrease was especially marked in the 0-5 cm layer with a 25% decrease (**Table S3**). Overall, the soil contained a small volume of coarse elements (> 2 mm, rock and roots), leading to a median fine earth fraction (FE) of 99% in 2005 and 2019. The mean FE fraction in 2019 was however lower (96%) due to a few samples showing as much as 58% coarse elements. The area excluded from the analysis shows a much higher rock fraction with a mean FE of around 90% and a significant number of samples with FE between 80% and 90%. Overall when excluding this area, the fine earth fraction averages 0.98 down to 30 cm depth and 0.94 below. These numbers are very similar to the fine earth fraction reported in 2005. We note also that the fine earth mass in the 0-60 cm was smaller by less than 3% in 2019 compared to 2005, a value close to the confidence interval (**Table S3**).

The SOC contents were similar in both campaigns, with a density distribution showing two peaks, one around 5 g C kg^{-1} corresponding to the bottom layers and one around 20 g C kg^{-1} corresponding to the surface layer. The latter peak showed a slight increase of around 1 g C kg^{-1} in the reduced area of 2019 compared to 2005. The excluded area showed SOC above 25 g C kg^{-1}, corresponding to the less dense samples (**Figure 4,** difference between "2019 reduced" and "2019"). Overall, the SOC content was significantly higher in 2019 than 2005 in the 0-5 cm (**Table S3**).

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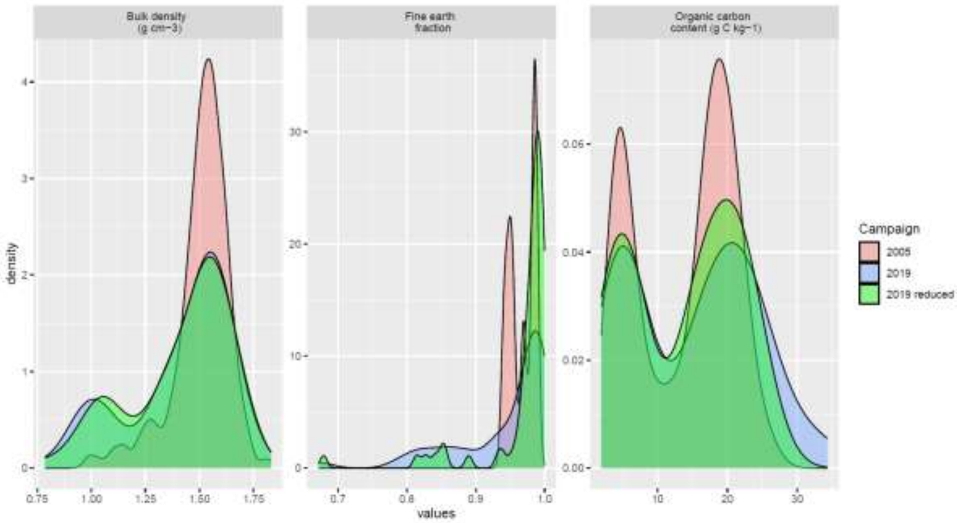

Figure 4. Density distribution of soil bulk density, fraction of fine earth in soil, and soil organic carbon content (named SOC_{fe} in the text) for all sampling depths considered together in the two campaigns (2005 and 2019) as well as for the reduced area in 2019 which was chosen so that the fine earth content was similar as in 2005.

3.2 Profiles of bulk density, carbon content and carbon stock

The BD decreased significantly between 2005 and 2019 in the 0-5 cm and 5-15 cm layers (**Figure 5**). BD's 0-5 cm layer was 1.30 g cm^{-3} in 2005 and 1.02 g cm^{-3} in 2019 (**Table S3**). In the 5-15 cm layer, the BD estimates varied from 1.48 to 1.57 g cm^{-3} in 2005, while they ranged from 1.36 and 1.52 g cm^{-3} in 2019. The BD was not significantly different between the two campaigns at lower depths. The decompaction was significant in the 0-15 cm layer, with a 25% decrease in BD in the first 5 cm and a 10% decrease in the 5-15 cm.

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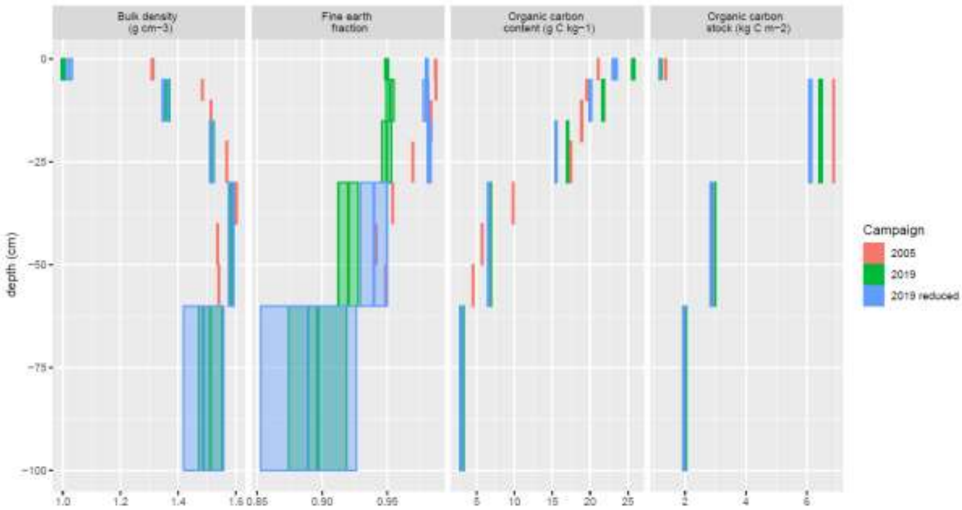

Figure 5. Profiles of bulk density (BD), fine earth fraction, soil organic carbon content (SOC_{fe}), and organic carbon stocks in the two campaigns. Ribbons show the 95% confidence interval calculated computed with eq. 9, and lines show means. A graph showing the organic, inorganic and total carbon stocks for 2019 is shown in Figure S1. Note that here, the carbon stocks are calculated at fixed depths.

The SOC content was also significantly different between the two campaigns in the 0-5 layer: it was 2.2 g C kg^{-1} higher in 2019 than in 2005 on average when considering the reduced area and 4.7 g C kg^{-1} higher when considering the whole field. The SOC content was also significantly higher in the 5-15 cm in 2019 than in the 5-10 and 10-20 cm layers in 2005 by roughly 2 g C kg^{-1} when considering the whole field but the difference was only slightly significant and smaller than 1 g C kg^{-1} when considering the reduced area more representative of the 2005 sampling (**Figure 5, Table S3**). The stratification observed in BD and SOC content leads to a strong correlation between the two components in the 0-30 cm layer. This leads to a constant bulk density of around 1.6 g cm^{-3} for the range of SOC content below 20 g C kg^{-1} and a decrease of the bulk density to lower than 1 for SOC content above (**Figure S2**).

Despite this higher SOC content in 2019, the SOC stock diminished in the upper layers, compared to 2005. On average, the SOC stock diminished by -200 ± 40 g C m^{-2} in the 0-5 cm layer, -770 ± 120 g C m^{-2} in the 5-30 cm layer, and increased not significantly in the 30-60 cm layer (+10 ± 140 g C m^{-2}) between the two sampling dates in the reduced area. If the less representative complete field is considered, the changes are -150 ± 40 g C m^{-2}, -430 ± 130 g C m^{-2}, and +80 ± 40 g C m^{-2}, in the 0-5, 5-30 and 30-60 cm layers respectively (**Figure 7**, **Table S4**). Overall the 0-30 and 0-60 cm stock decreased significantly by -970 ± 140 g C m^{-2} and -960 ± 220 g C m^{-2} between 2005 and 2019 in the reduced area, a value twice as large as if the whole field is considered (-510 ± 230 g C m^{-2} in the 0-60 cm).

The inorganic carbon stock was reported to be negligible compared to the organic carbon stock in 2005, which is also what we find in 2019 for depth smaller than 30 cm. In the 30-60 cm depth, in reduced area in 2019, the inorganic carbon stock was however on average of the same order of magnitude than the organic carbon stock (**Figure S1**), although the median is negligible (0.34 kg C m^{-2} compared to 2.9 kg C m^{-2} medians). In the 60-100 cm layer, the inorganic carbon stock was significantly larger than the organic carbon (more than 55 kg C m^{-2}

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compared to 2 kg C m^{-2}) in the reduced area . Below 60 cm, the inorganic carbon stock becomes a component that should be considered therefore thoroughly when monitoring carbon stock changes over the complete field.

3.3 Soil carbon stock change over time

The SOC stock in the 0-60 cm layer of soil was 11.1 ± 0.19 kg C m^{-2} in 2005, a value significantly higher by 0.96 kg C m^{-2} than that measured in 2019 (10.2 ± 0.32 kg C m^{-2}). The same observation holds with the ESM method, with a difference of 0.92 kg C m^{-2} between the two campaigns (**Figure 6**, **Table S4**). The main reason for the observed C stock change seem to be the reduction of the bulk density, especially in the 0-15 cm layer, and a slight reduction of the carbon content in the 15-30 cm layer (**Table S3**). The difference is significant ($p < 1e-3$) despite the lower number of samples in 2019 (14 for the reduced area) than in 2005 (100). However, in 2019, the designed-based inference reduced the estimated mean (sampling variance) uncertainty for a few points. Using the entire field sampled in 2019 instead of the reduced area around the field sampled in 2005 would lead to a large biased C stock change of only -0.51 ± 0.23 kg C m^{-2} with the fixed depth method and even less -0.37 ± 0.21 kg C m^{-2} with the ESM method (**Figure 6**, **Table S4**). This bias seems to be mainly explained by a higher carbon content in the excluded area in 2019, but since this area was not measured in 2005 it is not possible to evaluate how it changed. The larger ratio of ESM to Fixed depth for the complete field can be attributed to the slightly smaller fine earth fraction in the excluded field in 2019 (**Table S3**). Overall, when considering the reduced area, the SOC stock diminished by around 72 ± 17 g C m^{-2} yr^{-1} over the 13.25 years period. Considering the ESM method would lead to a difference of 70 ± 16 g C m^{-2} yr^{-1}, which is only 2 g C m^{-2} yr^{-1} smaller (**Figure 6**). The fact that the ESM is close to the fixed depth method is consistent with the fact that the carbon stock change is mostly observed in the 0-30 layer, or in other words that the carbon stock change in the 30-60 cm layer is negligible. This indeed means that the correction to apply for soil mass changes is small. On the contrary, the ESM estimation is less than half of the fixed depth estimation of soil stock in the 0-30 cm layer (**Figure S3**). Moreover, the ESM estimations indicate that only 45% of the soil stock changes occurred in the 0-30 cm layer depth compared to the 0-60 cm layer. The fact that the ESM and fixed depth estimations are close to each other in the 0-60 cm layer indicates that, although the 30-60 cm layer does not contribute significantly to the soil stock change, it is essential as to provide a robust estimate of the soil stock change.

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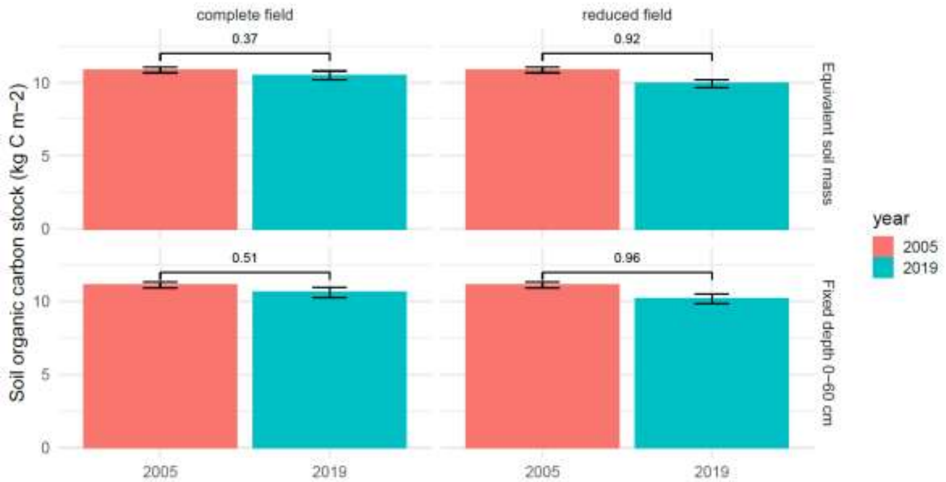

Figure 6. Organic carbon stock measured in 2005 and 2019 over the 0-60 cm layer with the fixed depth (lower panels) and equivalent soil mass (upper panels) methods. For 2019, the complete field or a reduced area most corresponding to the 2005 sampling area are considered. The error bars show the 95% confidence interval calculated according to eq. 9. Figure S3 shows the carbon stock over the 0-30 cm layer.

Decomposing this SOC stock change over the different layers (**Figure 7**) shows that 20% of the change comes from the 0-5 cm layer, and 80% from the layer 5-30 cm, while the 30-60 cm showed a slight but non-significant increase of 1%. The stock change per unit depth observed in the 0-5 cm and 5-30 cm layers where similar in magnitude though slightly higher in the 0-5 cm (-40 g C m^{-2} cm^{-1} and -30 g C m^{-2} cm^{-1}).

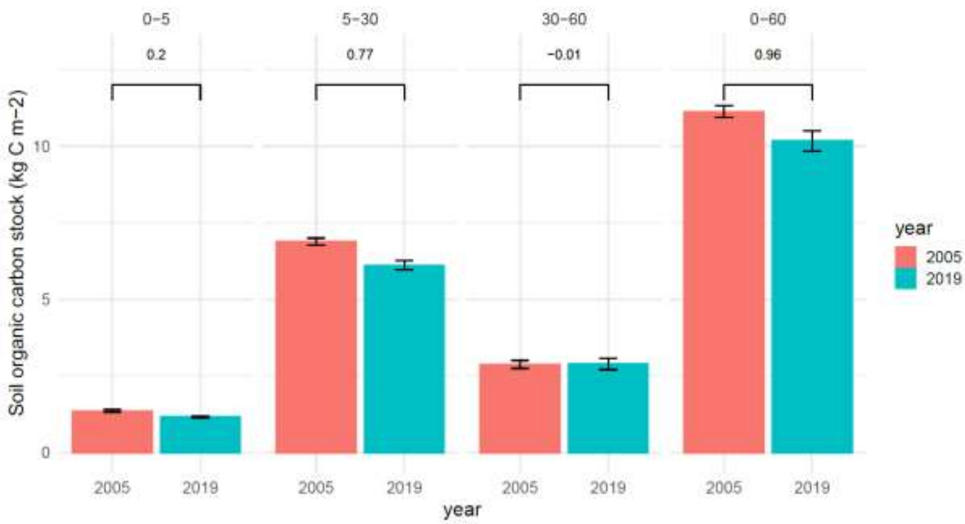

Figure 7. Carbon stock evolution between 2005 and 2019 over different layers with the fixed depth method (FD) over the reduced area. The error bars show the 95% confidence interval calculated according to eq. 9.

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3.4 Comparison of measured SOC stock changes with estimations obtained with the AMG model

The AMG model was used to simulate the soil organic carbon stock evolution from 2005 to 2040 in the 0-30 cm layer, based on cropping system, imports and exports computing the plant residues return based on allometric relationships. The AMG outputs simulations are in very good agreement with the organic carbon stock change measured by the fixed depth method in the 0-30 cm depth (**Figure 8**). The flux balance approach computed from 2006 to 2010 as reported by Loubet et al. (2011) is also very consistent with the AMG model in showing a steep decrease in carbon stock during that early period. Since the 0-30 cm layer represents ~100% of the region where the organic carbon stock change occurred (**Figure 7**), this result indicates all three estimations therefore converge in showing a decrease of the same magnitude of ~70 g C m^{-2} yr^{-1} over the 2005-2019 period. The AMG model further shows that if the crop rotation, exports and imports are repeated in the next years as in the 2005-2019 period, the organic carbon stock in the soil would stabilize around 7 kg C m^{-2} in the 0-30 cm layer, which means around 13 kg C m^{-2} in the 0-100 cm layer if the 30-100 cm does not lose carbon in the mean time.The overall loss over a 22 year period would then be of around 1.25 kg C m^{-2}, or 12.5 t C ha^{-1}, which amounts 570 kg ha^{-1} yr^{-1}.

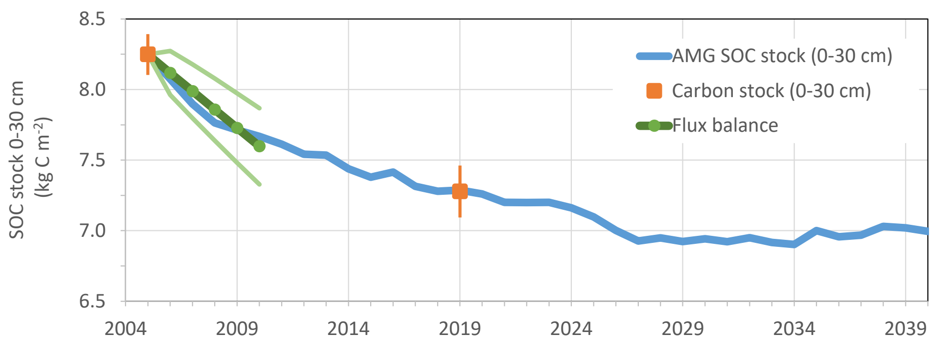

Figure 8. Soil organic carbon stock in the 0-30 cm depth as simulated by the AMG model (blue), measured by soil sampling in 2005 and 2019 with the fixed depth method (orange squares), and measured by flux balance over the 2006-2010 period (green points and light green line for error bars) as published in Loubet et al. (2011). The error bars show the sampling standard error. The 2019 soil stock is given for the reduced field only.

4 Discussion

4.1 Effects of sampling depth and computation methods on organic carbon stock changes evaluation

Du et al. (2017) argued that although no-tillage experiments led to an apparent gain in C storage compared to conventional tillage, most studies were biased because of shallow sampling (15 cm) and fixed-depth method. Indeed, the combination of fixed depth and shallow sampling led to a systematic overestimation of carbon storage in no-till systems. Meurer et al. (2018) concluded that no-till might lead to limited carbon storage (10 g C m^{-2} yr^{-1}) when considering a 0-60 cm layer compared to till systems, with considerable uncertainty (-2 – 50 g C m^{-2} yr^{-1} 95% confidence interval). Although our study does not allow us to estimate the 0-15 cm layer SOC change, it confirms that measuring down to 30 cm was critical to capture soil stock changes in our field as 80% of the carbon stock changed occurred in the 5-30 cm layer. Moreover, our study shows that measuring at only 30 cm depth leads

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to very large differences between the ESM and the fixed depth estimations while the two methods agree within 3% in the 0-60 cm layer (**Table S4, Figure S3**). This indicates that measuring down to 60 cm would lead to more robust estimations of the soil carbon stock changes.

Baker et al. (2007) indeed emphasised the need to sampling deep enough to measure SOC stock changes over time. Indeed, the root system goes well beyond 5 cm and 30 cm, and its structure is bound to change with tillage practice and bulk density changes. This was observed for maize(Tardieu, 1988) and wheat (Zhang et al., 2020; Zuo et al., 2006), the main crops in this cropping system. Roots receive a significant fraction of carbon originally photosynthesised through translocation to develop their structure. Part of this translocated carbon may be released in the soil as rhizodeposition, representing around 30% of the C allocated to roots and around 10% of the whole C assimilated by plants (Dignac et al., 2017). It is, therefore, essential to sample the soil deep enough to catch most of the root exploring zone. Fan et al. (2016) reported that most crops would have 95% of the root biomass above 100 cm depth, which is a good compromise depth. Our results show that the C stock has significantly diminished in the 0-5 and 5-30 cm layers taken individually but not in the 30-60 cm layer (**Figure 8**), demonstrating the need to sample down to 30 cm at least in this soil. Sampling to lower depth also has the advantage of diminishing the potential bias of using fixed depth sampling. Indeed, our results show little difference between ESM and FD estimates of SOC stock in the 0-60 cm layer. This is due to a combination of small BD at the surface layer and small SOC content below 60 cm depth, leading to a small SOC stock compensation of the missing soil mass by increasing sampling depth. This result was also found by Xiao et al. (2020), which showed that FD and ESM led to similar estimates of organic carbon stocks as long as the sampling depth was large enough.

4.2 SOC stock changes are significantly detected over the 15 years

We found a change in SOC stock of 960 g C m^{-2} in the 0-60 cm layer over the 13.25 years spanning the two campaigns. The confidence interval of SOC stock measurement ranges between 190 g C m^{-2} for the 2005 campaign and 320 g C m^{-2} for the 2019 campaign (in the 0-60 cm layer, **Table S5**). Schrumpf et al. (2011) predicted a minimum detectable difference (MDD) larger than 105 g C m^{-2} in the 0-10 cm layer and 263 g C m^{-2} in the 0-30 cm layer. Our study shows a change of more than three times this value over 15 years, indicating that a shorter revisit time between campaigns may have been applied for this intensive crop site with a high initial carbon content. A 10-year revisit would have been appropriate for this site but may not be sufficient in the future as suggested by soil carbon stock modelling that shows a stabilisation of the soil carbon stock to a new equilibrium around 2028 with a foreseen change of only 250 g C m^{-2} (**Figure 8**).

4.3 Comparison with other studies on SOC stock changes in crops

In this study, we found an average carbon loss of 72 ± 17 g C m^{-2} yr^{-1} over the 15 years in the 0-60 cm soil layer on this wheat-barley-mustard-maize crop rotation with oilseed-rape replacing barley twice, and cover crop being always present before maize cultivation. The average yearly export from the field was 470 ± 54 g C m^{-2} and the field received quite a large amount of organic fertilisation with an average 114 ± 13 g C m^{-2} and a residue return of 151 ± 17 g C m^{-2}. Keel et al. (2019) found between 10 and 135 g C m^{-2} yr^{-1} loss in a range of crops in Switzerland, averaging 34 g C m^{-2} yr^{-1}. They observed the highest losses (135 g C m^{-2} yr^{-1}) over a crop rotation similar to our study, cultivated intensively, but on an Orthic Luvisol that had an initial SOC stock similar to our study (~ 7 kg C m^{-2} in the 0-20 cm layer). In their work, the high C losses were attributable to the recent conversion from

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grassland with a high SOC stock to a crop with a lower SOC stock, which may explain the doubled carbon stock change compared to this study. We note that in Keel et al. (2019), the amount of C input to the soil as residue return and organic fertilisation ranged from 90 to 320 g C m^{-2} yr^{-1}, a range similar to our study (265 ± 30 g C m^{-2}).

Knotters et al. (2022a) found a decrease in SOC content by 8 g C kg^{-1} in the 0-30 cm layer and 18 g C kg^{-1} in the 30-100 cm layer of croplands over the 1998-2018 period in the Netherlands. A lower decrease was observed in grasslands over the same region in the 0-30 cm layer (4.7 g C kg^{-1}). They evaluated an average SOC change of 190 g C m^{-2} yr^{-1} over that period in the 0-100 cm layer, a change three times larger than what we observed in this study. However, they did not provide any uncertainty for their estimations and they indicated that bulk density was too uncertain to give confidence in their stock changes estimations.

Van Wesemael et al. (2010) found an average decrease of 22% of the SOC stock over 46 years over crops in Belgium, corresponding to a loss of 0.4% yr^{-1} of the SOC stock, a value lower than what we find in this study (0.6% yr^{-1}, **Table S5**). They estimated that half of these losses could be attributed to the average erosion of 13 mm yr^{-1}, which truncated SOC's richer topsoil and deepened the ploughing depth. Van Wesemael et al. (2010) exhibited residue returns and organic inputs in loamy soils similar to what we report here, around 350 g C m^{-2} yr^{-1}.

Bellamy et al. (2005) found a loss of 0.6% yr^{-1} of the SOC in England and Wales over 25 years in the 0-15 cm layer. They further found a loss that increased with the original carbon content. A criticism that can be done to the latter study is the shallow sampling, down to 15 cm. This may indeed lead to misinterpreting a change in soil density as a carbon stock change, and a carbon transfer to lower depths as a carbon loss. We notice that we found a similar SOC stock change in the same 0-30 cm layer in our study.

Mary et al. (2020) found a stable SOC stock over 45 years in the 0-30 cm layer, whatever the tillage intensity in a winter-wheat-maize rotation. They found that surface-till led to an increased carbon stock in the 0-10 cm but a decrease in the 10-30 cm SOC stock, while we found a decrease in the two top layers. In our study the maize crop was used for silage, hence leading to smaller amounts of residues returning to the ground (**Table 1**) which would explain the difference compared to Mary et al. (2020). Indeed, during the 45 years of their study, Mary et al. (2020) and Dimassi et al. (2014) found a decrease in the SOC stock when the residues return was diminished and when maize was removed from the rotation (winter wheat, winter barley, sugar beet and pea). Overall, the SOC loss rate reported during these periods in the 0-30 cm layer ranged from 18 to 76 g C m^{-2} yr^{-1} (Dimassi et al., 2014), an amount in the range of what we found here. Their work together with our study both suggest that limited residue return rates may lead to an increase carbon loss from the soil.

4.4 Changes in SOC stock over time and organic carbon stock equilibrium

The relative change in SOC stock reported in this study is about 0.6% $year^{-1}$ in the 0-60 cm, similar to previous work at the country level (Bellamy et al., 2005) or the field scale (Ceschia et al., 2010). One explanation for this observed decrease in the carbon stock is that the site C supply was in disequilibrium, even if the soil received an average C import and residue return of 265 g C m^{-2} yr^{-1} (114 + 151 g C m^{-2} yr^{-1}, **Table 1**). The losses may indeed be explained by the imbalance between losses due to respiration of this soil containing a high content of organic matter, and low inputs due to high biomass exportation rates, around 3 times higher than imports and 2 times higher than the import and aerial residue return combined (470 g C m^{-2} yr^{-1} on average). Maize rotations were also shown to lead to high mineralisation rates after harvest (Ceschia et al., 2010; Loubet et al., 2011), firstly due to a

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shorter cultivation period and possibly increasing mineralisation rate by adding fresh organic matter. These losses indicate that the soil carbon stock was not in equilibrium with the imports and exports used in the cropping system applied. The fact that the simple AMG model that accounts for these imports and exports successes in modelling the carbon balance evolution is a clear confirmation that this imbalance is the most plausible cause for the observed organic C stock change (**Figure 8**). This field was cultivated with crops for over 100 years, so it is excluded that the change comes from a change in crop cultivation. However, the field received large amounts of organic matter in the 1980s from waste treatment plans, although the exact amount was not recorded. Furthermore, since 2004, the field started to export more wheat straw than previously for bioenergy use. This historical change in management of the field may therefore have led to SOC stock decrease by limited crop residue return and lower organic imports. The AMG simulation further suggests that the SOC stock should diminish at the same rate until 2028 and then stabilise.

The integrated carbon fluxes from 2006 to 2010 (Loubet et al., 2011) confirm a carbon loss from the soil similar to the AMG simulations during that period (**Figure 8**). Although the uncertainties on the integrated carbon fluxes are very large, the coherence between the two approaches corroborates the large soil carbon loss in the years 2005-2010 which is consistent with the small organic carbon fertilisation and residue return during that period. We also note that the yearly carbon loss from Loubet et al. (2011) is not significantly different from the yearly carbon soil destocking found in the present study. Leifeld et al. (2011) also compared the integrated carbon fluxes and soil sampling methods over 5 years on an intensive and an extensive grassland, both recently converted from intensive cropland. They concluded that the large uncertainties in both methods prevented detecting a significant change over 5 years in the intensive field. On the contrary, in the extensive field, they found a significant decrease of the SOC stock of -217 ± 143 g C m^{-2} yr^{-1} by soil sampling, but a lower loss of -65 ± 92 g C m^{-2} yr^{-1} based on the integrated carbon fluxes method. We note that in Leifeld et al. (2011) and in our study, the two methods provide yearly losses that are not significantly different from each other.

4.5 Uncertainties in soil inorganic carbon stocks changes

Previous measurements of carbon leaching at the FR-Gri site indicated that inorganic carbon contributed to the soil carbon losses at the site. Indeed, Kindler et al. (2011) showed that, in 2010, the site was losing 28 g C m^{-2} yr^{-1} through leaching with a contribution of 21 g C m^{-2} yr^{-1} as dissolved inorganic carbon (DIC). Dissolved organic carbon leaching was evaluated to contribute to the overall organic C loss from the field to around 10% (Loubet et al. 2011). We should however recall that even if C is lost by DIC-DOC leaching from the 0-60 cm layer, it may lead to a deep C sequestration by formation of secondary $CaCO_3$ (Liu et al., 2022; An et al., 2019). Nevertheless, inorganic carbon leaching dominates at the site, with 75% of the leached C being inorganic, indicating a clear carbonate dissociation to DIC leaching, due to H^+. Although not measured directly as a soil stock change, we can therefore evaluate that carbonate leaching would lead to an additional inorganic soil carbon loss of 21 g C m^{-2} yr^{-1}, leading to a total of 72 + 21 = 93 g C m^{-2} yr^{-1} carbon loss. The inorganic carbon loss would therefore represent a very significant amount of 22% of the total carbon lost from the field, which could be induced by nitrogen fertilisation and base cations exports by harvest (Raza et al., 2021; Song et al., 2022; Zamanian et al., 2021). The FR-Gri crop received 193 kg N ha^{-1} as half organic, half mineral fertilisation and exported 470 g C m^{-2} yr^{-1} (**Table 1**). These N fertilisation and exportation would lead to significant H^+ production, though not quantified. Hao et al. (2019) reported a proton production of 13 kmol H^+ ha^{-1} yr^{-1} in intensively fertilised crops in China, while Guo et

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al. (2010) showed that nitrogen cycling and base cation uptakes contributed to a release of more than 50 kmol H^+ ha^{-1} yr^{-1} in highly fertilised wheat, a crop similar to our site in terms of management. Hence, it is likely that inorganic carbon losses would occur in FR-Gri.

Raza et al. (2021) further pointed out that carbonate dissociation may also lead to gaseous CO_2 production, which could then escape from the soil when this dissociation occurs in the surface layer or be dissolved in water when this happens deeper in the soil. In principle, this gaseous CO_2 emission would be interpreted as a respiration term, but would represent a quite small fraction: 21 g C m^{-2} yr^{-1} would represent around 2 to 3% of the annual terrestrial respiration measured at the site (Loubet et al., 2011). Whether a gaseous CO_2 flux of that small amount could be detected by the flux balance method still requires to be demonstrated. The amount of inorganic carbon losses by leaching or gaseous emissions in fertilised crops over soils with a significant inorganic carbon stock as in FR-Gri should therefore be further monitored in the future.

5 Conclusions

A significant decompaction of the 0-15 cm soil layer was observed over the 15 years in this crop field, with an estimated 25% decrease in bulk density in the 0-5 cm layer and a 10% decrease in the 5-15 cm layer. This decompaction can be attributed to reduced deep tilling and increased intercropping since 2005. Significant increases of organic carbon content of around 15% in the 5-15 cm layer and 20% in the 0-5 cm layer were observed.

However, despite the higher SOC content, the carbon stock decreased significantly in the 0-5 cm and 5-30 cm layers, but not in the 30-60 cm layer. Overall, the SOC stock decreased by 960 ± 220 g C m^{-2} (uncertainty shows confidence interval) over the 13 years in the 0-60 cm layer. The SOC stock did not differ significantly when calculated by the equivalent soil mass (920 ± 210 g C m^{-2}) in this 0-60 cm layer. This small difference can be explained by the fact that sample was performed at a sufficient depth of 60 cm to minimise the biases. Considering the 0-30 cm layer led to a significant difference between the equivalent soil mass and fixed depth approach further demonstrating the need to sample deeper than 30 cm to strengthen the robustness of the soil carbon stock evaluation.

Overall, we observed an annual SOC stock decrease of 72 ± 17 g C m^{-2} yr^{-1} on average over the 13.25 years in the 0-60 cm soil layer. This organic carbon loss which amounts -6.5 per mil yr^{-1} is in line with other studies and well reproduced by the AMG model simulations itself consistent with the flux balance approach over the 2005-2010 period. Our study therefore indicates that low-till, intercropping, and organic fertilisation may not be sufficient to prevent soil carbon losses in situations where the initial SOC stocks are high and residue return is limited. As confirmed by other studies, the losses observed here indicates that the 4-per-mille aspirational target would be difficult to reach in cropping systems representative of the Parisian region characterised by large soil organic carbon stocks.

Our study calls for high-quality SOC stock evolution measurements combined with integrated carbon fluxes as developed by the ICOS research infrastructure, in order to better understand the underlying processes behind soil C stock changes. In this prospect, inorganic carbon loss both by leaching and gaseous CO_2 effluxes remains uncertain and would require further evaluation at sites with carbonaceous soils such as FR-Gri or other ICOS sites.

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Code/Data availability

The 2019 campaign report and data are accessible on the ICOS carbon portal (Buysse, 2023) and there https://traitementinfosol.pages.mia.inra.fr/icos/FR-GriCarbonReportv2.html. The 2005 campaign data are accessible as Asset. The script, and all data are given as Assets.

Authors contribution

BL conceptualised, supervised, acquired the funding for the study and administrated the project. BL and MG prepared the original draft of the manuscript with the contribution from all co-authors, and revised it. NS provided the formal analysis, provided the statistical expertise and scripts to compute the carbon stocks. The scripts were developed by MG and verified by BL. PB made the soil sampling and data curation for the 2019 campaign, curated the crop management data and reviewed the manuscript. JPC and NS participated in the ICOS database data curation. CD managed the soils storage in 2019, contributed to data curation, and reviewed the manuscript. CJ provided expertise on the soil sampling methodology.CK made data curation on the crop management data and reviewed the manuscript. FL computed the AMG and reviewed the manuscript. JLME provided expertise on the ESM methodology and reviewed the manuscript. SL participated in data curation and reviewed the manuscript. DL and DP conceptualised the data acquisition and reviewed the manuscript. GN participated in the data curation. Bruna Winck contributed to data curation and validation and reviewed the manuscript. DA initiated the project, conceptualised, developed and provided expertise on the methodology and revised the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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