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Reduced tillage in organic farming affects soil organic carbon stocks in temperate Europe

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ABSTRACT

For decades, conservation tillage has been promoted as a measure to increase carbon stocks in arable soils. Since organic farming improves soil quality and soil carbon storage, reduced tillage under organic farming conditions may further enhance this potential. Therefore, we assessed soil organic carbon (SOC) stocks of reduced tillage compared with mouldboard ploughing in nine organic farming field trials in France, Germany, the Netherlands, and Switzerland with the same sampling and analytical protocol. We sampled soil cores until a depth of 100 cm to determine soil carbon stocks that are relevant for climate change mitigation but are often overlooked in tillage studies with shallow sampling depths. The studied field experiments were between 8 and 21 years old and comprised different soil types with clay contents ranging from 10% to 50%. SOC stocks increased with increasing clay-to-silt ratio, precipitation and organic fertiliser input. Across sites, reduced tillage in comparison with ploughing increased SOC stocks in the surface layer (0–10/15 cm) by 20.8% or 3.8 Mg ha^{-1}, depleted SOC stocks in the intermediate soil layers to 50 cm soil depth with a maximum depletion of 6.6% or 1.6 Mg ha^{-1} in 15/20–30 cm and increased SOC stocks in the deepest (70–100 cm) soil layer by 14.4% or 2.5 Mg ha^{-1}. The subsoil SOC stock increase may be linked to the inherent soil heterogeneity. Cumulative SOC stocks increased by 1.7% or 1.5 Mg ha^{-1} (0–50 cm, n = 9) and 3.6% or 4.0 Mg ha^{-1} (0–100 cm, n = 7) by reduced tillage compared with ploughing with estimated mean C sequestration rates of 0.09 and 0.27 Mg ha^{-1} yr^{-1}, respectively. There was no effect of field trial duration on tillage induced cumulative SOC stocks differences. Under reduced tillage, biomass production was 8% lower resulting in a decrease of crop C input by 6%. However, this reduction may have been outbalanced by increased C inputs from weed biomass resulting from a higher weed incidence in reduced tillage, which warrants further research. Thus, reduced tillage in organic farming has the potential to increase total SOC stocks, while crop management has to be improved to increase productivity.

Abbreviations: BD, bulk density; CT, conventional tillage, mouldboard ploughing; ESM, equivalent soil mass modelling of soil organic carbon stocks; FD, fixed depth calculation of soil organic carbon stocks; MASL, metres above sea level; NT, no-till, direct seeding; RT, reduced tillage; SOC, soil organic carbon.

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1. Introduction

Climate change is forcing mankind to change current management practices in many fields, including agricultural production. Mitigation and adaptation are crucial to sustaining food security for future generations (Vermeulen et al., 2012). There is increased interest in the sequestration of atmospheric CO_2 as carbon into degraded agricultural soils as a tool for climate change mitigation (Chenu et al., 2019). Moreover, soil organic carbon (SOC) is vital for climate change adaptation as it is linked to soil structure formation that is crucial for water infiltration and storage, besides erosion control (Mondal et al., 2019).

Various management strategies are discussed for SOC sequestration. Crop rotations and residue return (Govaerts et al., 2009), additional cover crops (Poeplau and Don, 2015) and organic inputs (Vandenbygaart et al., 2003) have been shown to sustain or even increase SOC stocks. Organic farming as a system approach includes those practices. A global meta-analysis on studies of mainly temperate regions found that organic farming increased SOC stocks in in the topsoil (0–20 cm) on average by 3.5 Mg C ha^{-1} (204 pairs) or 0.45 Mg C ha^{-1} yr^{-1} (41 pairs) compared to non-organic management (Gattinger et al., 2012).

Conversion of deep soil inversion by ploughing (conventional tillage, CT) to a no-till (NT) management redistributes SOC within the soil profile with SOC enrichment in the surface layer (Luo et al., 2010). NT has been promoted to sequester carbon for years (Ogle et al., 2019). Yet, meta-analyses show only a small and insignificant overall increase in total SOC stocks by NT over CT (Luo et al., 2010; Meurer et al., 2018) and there is evidence that soil types and climatic conditions impact the sequestration strength (Ogle et al., 2019). Since meta-analyses report several shortcomings of original studies they are based on, e.g. sampling depth or data reporting quality (Luo et al., 2010; Meurer et al., 2018), the real effect of NT or in general of conservation tillage on SOC sequestration is still not evident.

Assuming that conservation tillage has a positive effect on SOC stocks, integration of NT into organic farming may be a step forward towards an agricultural system with a high SOC sequestration potential and other beneficial effects, e.g. biodiversity (Mäder et al., 2002). However, successful NT that is continuously applied over the years is only possible due to herbicides use as weed control measure. Consequently, research in organic farming has mainly focused on reduced tillage (RT), where tillage is still applied for weed control (Zikeli and Gruber, 2017). RT is less clearly defined than NT since a variety of machines are commonly used. In Europe, RT can include ploughing or non-inversion tillage to shallow soil depths or superficial tillage with pulled or power take-off driven machinery if they are less intensive than traditional mouldboard ploughing (Cooper et al., 2016; Zikeli and Gruber, 2017). RT is also defined concerning residues left on the soil surface after sowing the next crop, with RT having a residue cover of 15–30% (CTIC, 2020). A first meta-analysis compiling 184 pairwise comparisons gathered under organic farming conditions globally showed that RT in comparison to CT (>25 cm) increased SOC stocks in the 0–30 cm soil layer by 1.4 Mg C ha^{-1} (Cooper et al., 2016). Yet, subsoils were not included, and the distribution of carbon within the soil profile was not assessed. The aim of this study was, therefore, to gain insights into the potential of RT to sequester carbon in organic farming. The comparison of RT with NT would have been helpful to detect which system performs better as a climate change mitigation measure, but to our knowledge, only one field trial exists with such a design (CH-1, Wittwer et al., 2017).

Regarding scientifically sound SOC stock determination, there are several technical issues to address: Blanco-Canqui et al. (2021) emphasise that sampling deep is crucial to assess tillage system effects on total SOC thoroughly. Another ongoing discussion concerns equivalent soil masses (ESM) in contrast to a fixed depth sampling approach for SOC stock determination (Ellert and Bettany, 1995). Von Haden et al. (2020) argues that the ESM approach is advantageous for tillage system comparisons and should be used onwards.

This study thus focused on generating SOC stock data to 100 cm sampling depth in nine long-term field trials that assess RT and CT under organic farming conditions. According to an internal standardised protocol, the same sampling preparation and collection was performed, and chemical analysis in the same lab assured data comparability. As trials were running from 8 to 21 years at the time of sampling, mid to long-term effects of tillage systems on SOC stocks were evaluated.

We hypothesised that under organic farming conditions, reduced tillage in contrast to ploughing i) will redistribute SOC stocks with an enrichment in the topsoil layer, but ii) will not significantly increase total SOC stocks. We also aimed to assess the ESM in contrast to the fixed depth approach for SOC stock determination.

2. Materials and methods

2.1. Site description

Nine sites situated in Switzerland, Germany, France and the Netherlands with a range of soil textures in the same climatic zone (Cfb – oceanic climate, Kottek et al., 2006) with field trials older than eight years were chosen for the common sampling. All trials were managed according to organic farming standards (European Union Regulation on Organic Food and Farming No. 834/2007, EEC, 2013). This means that no synthetic pesticides or fertilisers were used. A ploughed reference (CT) was compared with a reduced tillage treatment (RT) in all experiments. Basic trial information, including the varying tillage implements used for RT, crop rotations and pedoclimatic conditions, are listed in Table 1.

In Switzerland, the Farming System and Tillage experiment (FAST) (CH-1, 47°26’20"N, 8°31’40"E, 486 MASL) of Agroscope was initiated in 2009. It compares farming systems (conventional vs organic), tillage systems (intensive vs no or reduced tillage) and cover crops as factors in a completely randomised split-plot design with four spatial and two temporal replications (Wittwer et al., 2021). The Cambisol has a sandy, loamy texture and a moderate plant available depth (50–70 cm). Plots of the organic system with cover crops and the first temporal replication were included in this study. The Research Institute of Organic Agriculture (FiBL) maintains the Aesch trial (CH-2, 47°28′54.7"N, 7°34′46.6"E, 350 MASL) on a silt loam of Loess deposits, a Luvisol, since 2010. Factors were fertilisation nested in tillage with four spatial replicates in an incomplete block design. Plots fertilised with slurry at recommended rates were included for sampling. The Frick trial (CH-3, 47°51′20′N, 8°02′36′E, 350 MASL) was started in 2002 with three factors: biodynamic preparations nested in fertilisation nested in tillage, also in an incomplete block design with four replicates (Krauss et al., 2020). This trial was based on clay loam, a vertic Cambisol, on the bottom of a valley. The clay sedimented from the surrounding Jurassic hills with limestone bedrock. Plots with slurry application and without biodynamic preparations were sampled.

In Germany, Justus Liebig University of Gießen manages the organic arable farming experiment Gladbacherhof (D-1, 50°23′48"N, 8°15′00"E, 174 MASL) since 1998. On a haplic Luvisol with silt loam texture, the two-factorial experiment encompassed the factors farming systems and four tillage treatments in a split plot design with four replicates (Schulz et al., 2014). Plots of the mixed arable farming system with livestock were chosen for this study. The Bavarian State Research Centre for Agriculture runs the Neuhof trial (D-2, 48°46’38.8"N, 10°47’33.2"E, 520 MASL) and the Puch trial (D-3, 48°11’37.0"N, 11°12’57.4"E, 550 MASL) since 1997 with different tillage systems and cover crops in a complete randomised design with three replicates. Both trials were converted to organic farming standards in 2012. They differ in climate and soils, with a stagnic Luvisol on silt clay in Neuhof and a Cambisol on silt loam in Puch. Plots without cover crops were included in the sampling. The University of Hohenheim started the KH6 trial (D-4, 48°74′N, 9°19′E, 444 MASL) in 1999 on a haplic Luvisol with clay loam texture from Loess. A stubble tillage factor was nested in tillage systems with a split

Table 1
Site characteristics. The crop in the year of sampling is highlighted in bold letters. Rep – field replication.

Site	Institute	Trial	Trial start	Rep	Climate	Soil type	Crop rotation	Fertiliser type	Plough (CT)	Reduced tillage (RT)	Sampling depth
CH-1	Agroscope	FAST	2009	4	9.4 °C, 1054 mm	Cambisol on gravel or gravelly moraine	legume CC - **WW**/ legume CC - GM - FB - WW - 2 years GC – WW - GM	Dairy cattle slurry, Landor BioN 10%	20 cm	Disc harrow, rotary harrow, Cultivators (Fräse/ Geohobel) 5–10 cm	0–50 cm
CH-2	Research Institute of Organic Agriculture (FiBL)	Aesch	2010	4	10.5 °C, 990 mm	Haplic Luvisol on Loess	SM - FB - WW – **2 years GC**	Cattle slurry	18 cm	Chisel, 5–10 cm	0–100 cm
CH-3		Frick	2002	4	10.4 °C, 1030 mm	Stagnic eutric Cambisol on fluvial deposits	2002–2013: SM – WW/CC – SF – SP – 2 years GC; Since 2014: WW/CC - SM - SP - **2 years GC**	Dairy cattle slurry	18 cm	Chisel, skim plough, 5–10 cm	0–100 cm
D-1	Justus Liebig University Giessen	Organic Arable Farming Exp. Gladbacherhof	1998	4	9.3 °C, 654 mm	Haplic Luvisol on Loess	**2 years alfalfa-grass ley**, WW/legume CC – PO – WW/legume CC - RY	Rotted solid cattle manure	30 cm	Blade cultivator (30 cm), rotary harrow (15 cm)	0–100 cm
D-2	Bavarian State Research Center for Agriculture (LfL)	V505–505 Neuhof	1997	3	8.7 °C, 685 mm	Stagnic Luvisol on Loess	1997–2011: WW – TC – SB or WW – RS, 2012–2014: GC, since 2015: WW – OA – FB – **RY**	No fertilisation	25 cm	Chisel, 5–10 cm	0–100 cm
D-3		V501–505 Puch	1997	3	8.7 °C, 883 mm	Cambisol/ Luvisol on Loess	1997–2010: TC – WW – RS – WW or SB, 2011–2013: GM, GC, since 2014: FB - RY - GC - WW - **OA**	No fertilisation	25 cm	Chisel, 5–10 cm	0–100 cm
D-4	University of Hohenheim	UHOH KH6	1999	4	8.8 °C, 700 mm	Haplic Luvisol on Loess	from 2000 to 2018: SP – PO – TC – 2 years GC – WW – OA – FB – SP – SM – 2 years GC – WW – OA – FB – SP – SM – TC – 2 years GC – SM – Pea – RY – 2 years GC – **WW**	Composted solid sheep manure	25 cm	Chisel, 15 cm	0–100 cm
F	ISARA Lyon	Thil	2004	3	11.4 °C, 830 mm	Calcaric Fluvisol	GM/CC – SOY/CC – **WW**/CC	Pig bristle, feather meal	30 cm	Chisel, 5 cm	0–70 cm
NL	Wageningen University	BASIS	2010	4	10.0 °C, 800 mm	Fluvisol on marine sediments	PO – GC – CA or PK/ **CC** – SW/CC – CR – SW/FB CC	Composted solid cattle manure, dried chicken manure, dairy cattle slurry	25 cm	Chisel, 15 cm	0–100 cm

Crops include: CA – cabbage, CC – cover crop, CL – clover, CR – carrot, FB – faba bean, GC – grass-clover ley, GM – grain maize, OA – oat, PO – potato, PK – pumpkin, RS – rapeseed, RY – rye, SB – spring barley, SF – sunflower, SM – silage maize, SOY – soybean, SP – spelt, SW – spring wheat, WW – winter wheat, TC – triticale

plot design and four replications (Zikeli et al., 2013). Plots without additional stubble tillage were considered for sampling.

In France, ISARA Lyon maintains the Thil trial (F, 45°49'9.44"N, 5°2′2.62"E, 200 MASL) since 2004 with several tillage systems completely randomised with three replications (Vian et al., 2009). The sandy loam soil, a calcareous Fluvisol, ended at 70 cm depth on river sediments. The shallowest tillage management was chosen for the reduced tillage system in this study.

In the Netherlands, Wageningen University & Research (WUR) manages the BASIS trial since 2009 (NL, 52°32′N, 5°34′E, −5 MASL) on reclaimed land since 1957. The sandy loam of marine origin was classified as a Fluvisol. Trial factors included three soil tillage systems completely randomised in four replications in two parallel field experiments (organic and conventional farming systems) (Crittenden et al., 2014). Organically managed plots with solid manure and slurry application were sampled.

2.2. Soil sampling

Soil sampling took place in 2017 in D-1 and WUR and spring 2018 in CH-1, CH-2, CH-3, F, D-2, D-3 and D-4. In each trial, plots under CT and RT were sampled according to the varying number of field replications, shown in Table 1. In all trials, we sampled three soil cores per plot at random locations using a core sampler (sheath probe). Consequently, a total amount of 66 soil cores was sampled with the same device. Crops at the time of sampling were either cereals, green manures or grass-clover leys (bold in Table 1). The core sampler had a length of 100 cm and an inner diameter of 6 cm (Walter et al., 2016). The core sampler was hammered into the soil with an electrically driven percussion hammer and extracted with a hydraulic pump. When inserting the core sampler, the soil core was moved into a polyethene film liner that ensures the core's integrity once extracted from the probe. Each soil core was divided into five to six layers: two to three layers until 30 cm, then fixed in 30–50, 50–70 and 70–100 cm. We adjusted the thickness of the topsoil layers according to the current and previous tillage depths of the respective trial. For D-1, D-4 and NL, the top 30 cm were divided into two layers of 15 cm each. In D-2 and D-3, we sampled 0–10 cm and 10–30 cm. In CH-1, CH-2, CH-3 and F, the topsoil was divided into 0–10, 10–20 and 20–30 cm. In the trials F and CH-1, the soil sampling was limited to a depth of 70 and 50 cm, because the lower limit of the soil was reached and the underlying parent material consisted of coarse gravel that slowed the sampling process.

Compaction and stretching of the soil core occurred in loamy soils during the extraction process. We thus recorded the total length of each soil core and each layer to correct for these distortions. To adjust the sample thickness, the differences between the length of the entire soil core (100 cm) and the length of the sheath probe was linearly allocated to the lower 30–100 cm part of the core as proposed by Walter et al. (2016). The length of each soil layer and core was noted and the volume calculated.

2.3. Sample preparation

Soil cores were transported from the field to the respective partner institution, stored in a cooling room until further steps and processed by each partner according to an internal standard protocol. After drying the whole sample at 40 °C until constant weight, the samples were sieved to 2 mm to separate the coarse (>2 mm, gravel and stones) and the fine fraction (<2 mm, fine soil material). Coarse soil aggregates were destroyed during this step. The masses of both fractions were determined separately for bulk density determination. An aliquot of 10 g was taken from the fine fraction, weighed, dried in an oven at 105 °C until the weight was constant, cooled in a desiccator and weighed again. The residual water content was used to calculate the difference between the 105 °C dry mass and the 40 °C mass. A representative subsample was taken from the 40 °C dried fine fraction and finely ground with a ball or mortar mill. The 40 °C dried, 2 mm sieved and ground subsamples were sent to the Research Institute of Organic Agriculture FiBL for further analysis.

2.4. Soil analysis

All soil analyses except the determination of bulk density were conducted at the Research Institute of Organic Agriculture FiBL.

2.4.1. Bulk density

We determined the bulk density per soil core and layer of the fine fraction in accordance with Poeplau et al. (2017) based on the mass of the dried fine and coarse fraction mass and the volume:

$$BD_{\text{fine soil}} = (\text{mass}_{\text{whole sample}} - \text{mass}_{\text{coarse fraction}})/[\text{volume}_{\text{whole sample}} - (\text{mass}_{\text{coarse fraction}}/D_{\text{coarse fraction}})] \quad (1)$$

where BD fine soil was the bulk density of the fine fraction (g cm^{-3}); mass $_{\text{whole sample}}$ was the mass of the entire sample including coarse and fine material (g); mass $_{\text{coarse fraction}}$ was the mass of the coarse fraction (g); volume $_{\text{whole sample}}$ was the sample volume (cm^3) measured with the sheath probe diameter and the sample thickness for the representative layer, and D $_{\text{coarse fraction}}$ was the approximation of rock density, i.e. 2.6 g cm^{-3}. The coarse fraction (stones) was considered to be completely dried.

2.4.2. Organic carbon content

We determined the organic carbon content in two steps: First: The total carbon content of every ground sample was measured on two replicates by dry combustion in a VarioMax cube (Elementar Analysensysteme GmbH, Hanau, Germany); Second: We determined the inorganic carbon content of each sample after removing the organic fraction by heating an aliquot in a muffle furnace at 500 °C for 5 h. This sample was afterwards combusted in the same elemental analyser in order to receive the inorganic carbon content. The organic carbon content was then calculated by subtracting the inorganic carbon from the total carbon content.

2.4.3. Texture and pH analysis

To elucidate the spatial heterogeneity in all nine trials, the 2 mm sieved samples of the three soil cores in the first 30 cm were pooled per plot. In the pooled samples, pH was measured in a 0.01 M $CaCl_2$ solution, and texture was analysed by sieving and sedimentation (ISO 11277:2020).

2.5. Calculation of SOC stocks with the site-specific fixed depth (FD) and equivalent soil mass (ESM) approach

The fixed depth approach was based upon measured values, while the equivalent soil mass approach included modelling. A detailed assessment of both principles can be found in Von Haden et al. (2020). We adjusted both approaches to include information on rock content and to be able to run all calculations in R (R Core team, 2020).

Regarding the fixed depth approach (FD), SOC stocks were calculated using equation 8 of Poeplau et al. (2017) that was proposed to represent SOC stocks without neglecting the impact of rocks in the sample:

$$SOC_{\text{stock FD}} = SOC_{\text{content fine soil}} \times \text{mass}_{\text{fine soil}}/\text{volume}_{\text{whole sample}} \times h \quad (2)$$

where SOC $_{\text{stock FD}}$ was the amount of carbon stored in a given soil area (Mg ha^{-1}); SOC $_{\text{content fine soil}}$ was the percentage of soil organic carbon in the fine soil fraction (%); mass $_{\text{fine soil}}$ was the mass of the fine soil (<2 mm) dried at 105 °C (g); volume$_{\text{whole sample}}$ was the volume of the whole soil sample (cm^3), and h was the thickness of the assessed soil layer (cm).

SOC stocks based upon equivalent soil masses (ESM) were modelled with cubic spline regressions. As inspired by Von Haden et al. (2020), we first calculated the soil mass for each layer sampled:

$$M_{\text{layer}} = BD_{\text{fine soil}} \text{ x h x } 100 \quad (3)$$

with M $_{\text{layer}}$ (Mg ha^{-1}) as the soil mass of the respective layer, BD $_{\text{fine soil}}$ as the bulk density of the fine fraction (g cm^{-3}) and h as the layer thickness (cm). Including the bulk density (Eq. 1) assured that stone content was considered, which was relevant at some sites.

SOC mass was calculated as.

$$SOC_{\text{mass}} = M_{\text{layer}} \text{ x SOC content / } 100 \quad (4)$$

with SOC $_{\text{mass}}$ (Mg ha^{-1}), M $_{\text{layer}}$ (Mg ha^{-1}) and SOC content (%).

SOC masses per layer (x-axis) were plotted against the respective soil masses (y-axis) that were cumulated with soil depth (Fig. 1). Since we sampled three individual soil cores per plot, the dataset for cubic spline regression obtained three data points per soil layer which was a prerequisite for the use of the function gam(SOC $_{\text{mass}}$ ~ s(cumulative M

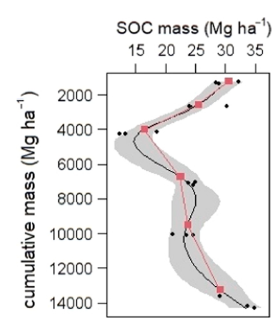

Fig. 1. Example of a cubic spline regression for the modelling of SOC stocks based on the equivalent soil mass approach. The spline (black line and grey 95% confidence intervals) based upon measured SOC masses with the fixed depth approach (black dots) is overlaid by SOC masses that are predicted at the mean cumulative mass of the reference treatment per soil layer (red squares, red line).

$_{layer}$), method= "ML", select=TRUE) of the “nlme” package (Pinheiro et al., 2020) in R (R Core team, 2020). To obtain SOC masses based upon the ESM method, the reference soil mass for each layer was defined as the mean cumulative soil mass of the ploughed plots (CT) per layer and site. The cubic spline algorithm per plot was then taken to predict the new SOC mass (=SOC $_{stock\ ESM}$) at each layer according to the defined reference soil mass with the function: predict(algorithm, newdata=reference soil mass). A minimal example of the ESM modelling is given as an R script in Appendix 1 (Supplement).

The cumulative SOC stock is finally the sum of all SOC stocks per layer to a defined depth, e.g. the SOC stock of 0–50 cm sums up all site-specific soil layers until 30 cm and the fixed layer 30–50 cm. This was done separately with SOC stocks obtained by the FD and ESM approaches.

As layers within the soil profile varied in thickness, normalisation of the FD SOC stocks with the respective layer thickness (cm) allowed for a direct SOC stock comparison between layers within the soil profile and sites in Mg ha $^{-1}$ cm^{-1}.

2.6. Estimation of crop biomass and aboveground C input

Crop type and marketable yields were available from all sites and all years, in addition to the information if crop residues or cover crops were removed or not. Regarding grass-clover leys, the cumulative yield of all cuts was considered. Most sites also reported crop residue (mainly straw) yields. If those were not available, crop residues were calculated using harvest indices that were either calculated from study data or supplemented by indices from literature (Table S1, Supplement). The residue biomass was calculated as:

$$YS = YP/HI - YP \quad (5)$$

with YS = Residue biomass (Mg dry matter ha^{-1}), YP = Grain biomass (Mg dry matter ha^{-1}) and HI = Harvest Index.

Average total biomass (Mg ha^{-1} yr^{-1}) was calculated by the sum of all biomass produced during the rotation, two biomass yields per year when cover crops are part of a rotation. The sum was then divided by the number of years where crop data were reported. The average biomass of grass-clover and cover crops was calculated accordingly based on the selected datasets. For the calculation of the aboveground organic matter input by residues, grain biomass was regarded as removed. For residues (straw or total plant biomass) left in the field, the whole residue biomass was accounted for. When residues were removed, 15% of the residue biomass was considered input by remaining stubbles and litter, as in Wiesmeier et al. (2014). Multiplying the average residue input with the C content of plants estimated to be 0.45 (Bolinder et al., 2007) gave the average C input by residues (Mg C ha^{-1} yr^{-1}). The percent share (%) of grass-clover, cover crops and residue input in the different rotations was calculated as the ratio of the respective average biomass to the average total biomass. Fertiliser C input was calculated from fertiliser type and amount per single application by the multiplication of dry matter input (Mg ha^{-1}) with C contents either measured in our study or gap filled with literature values (Table S2, Supplement). Analogous to average biomass, the sum of residue C inputs, fertiliser C inputs and their product were each divided by the number of years where data were reported to the average C input (Mg C ha^{-1} yr $^{-1}$).

Weed biomass was only assessed at some sites and in selected crop years. Data are thus less reliable. Average weed biomass per site (Mg ha^{-1} yr^{-1}) was estimated from the cumulative weed biomass divided by years assessed and the estimated C input (Mg C ha^{-1} yr^{-1}) by its multiplication with 0.45 (Bolinder et al., 2007).

2.7. Statistics

All statistical analyses were run in R (R Core team, 2020) version 3.6.1. Analyses of variance (ANOVA) were calculated with the “nlme” package (Pinheiro et al., 2020). FD SOC stocks and biomass data were tested for significant differences between tillage systems across sites, considering the sampled soil core nested in field replication nested in the site as a random effect. ESM SOC stocks could only be analysed on a plot basis with field replication nested in site as a random effect. Variation between sites was modelled with sites as variance covariate in the varIdent(form=~1|site) term. ANOVAs regarding every single site only included the sampled soil core nested in field replication (FD SOC stock, biomass) or field replication alone (ESM SOC stock) as a random effect and the tillage system as variance covariate. Variance homogeneity and normal distribution of residuals were assured with this approach. Linear regressions of SOC stocks with pedoclimatic conditions and management were assessed with the lm() function of the base package. All figures were made with the “ggplot2″ package (Wickham, 2016).

3. Results

3.1. Profile distribution of SOC stocks

In a relative comparison of RT and CT, RT stratified SOC contents (%) with an enrichment in the topsoil and reductions in 10/15–50 cm compared with CT (Fig. 2, Supplement Table S3). Bulk densities varied largely between sites in the topsoil and were higher in RT plots in all layers below, especially in the 10/15–30 cm layer. Consequently, a significant average enrichment in SOC stocks calculated with the fixed depth approach of + 21% or 3.8 Mg ha^{-1} in RT over CT was calculated across the nine sites in 0–10/15 cm, which represents the new tillage depth in RT after conversion from ploughing (Table 2). The increase in topsoil SOC stocks between RT and CT ranged from + 3% to + 44% depending on site and were significantly higher in RT in six out of nine sites (Table S4, Supplement). Below the 10/15 cm soil layer until a depth of 70 cm, lower absolute SOC stocks were recorded in RT than CT. The greatest reduction was observed between 15/20–30 cm with − 7% or − 1.6 Mg ha^{-1} lower stocks in RT compared with CT (Table 2). Yet, variation between sites was high, ranging from − 29% to + 14% (Table S4, Supplement). Higher SOC stocks in RT were again recorded in 70–100 cm (+14% or 2.5 Mg ha^{-1}) based on a lower number of trials that could be sampled to that depth. The seven sites that allowed sampling in 70–100 cm showed a 2–26% higher SOC stock under RT, which was significant at one site (NL) and tended to be higher at two sites (D-1, D-2) (Table S4, Supplement). ESM modelled SOC stocks deviated slightly from calculated FD stocks, and tillage differences at each site were less pronounced than the FD approach (Table S4). Yet, the stratification by RT relative to CT was confirmed with a significant increase in the topsoil layer and a reduction in 15/20–50 cm, which was significant for the 30–50 cm layer (Table 2).

In order to compare absolute SOC stocks between soil layers, tillage systems and sites, FD SOC stocks were normalised by the layer thickness (Mg ha^{-1} cm^{-1}) (Fig. 3, Table S3, Supplement). SOC stocks and their distribution with soil depth differed greatly between sites. The SOC distribution showed that agricultural management accumulated large amounts of SOC in the tilled layers with a steep decrease below. The typical tillage depth of approximately 20 cm at the Swiss sites and 25–30 cm at German sites can be traced in SOC stock distribution. The French and Dutch sites had a less pronounced stratification within the soil profile. The highest stocks were found in the clayey soil of CH-3. The sites CH-3, F and NL with fluvial or marine history had the highest subsoil SOC stocks.

3.2. Cumulative SOC stocks

Regardless of soil depth (0–30, 0–50, 0–70 or 0–100 cm) chosen to calculate cumulative SOC stocks, cumulative SOC stocks were higher in RT in comparison with CT across the nine sites sampled. This effect was significant in 0–30 cm and 0–100 cm for both calculation approaches and in 0–50 cm in tendency ($p < 0.1$) for the fixed depth approach and

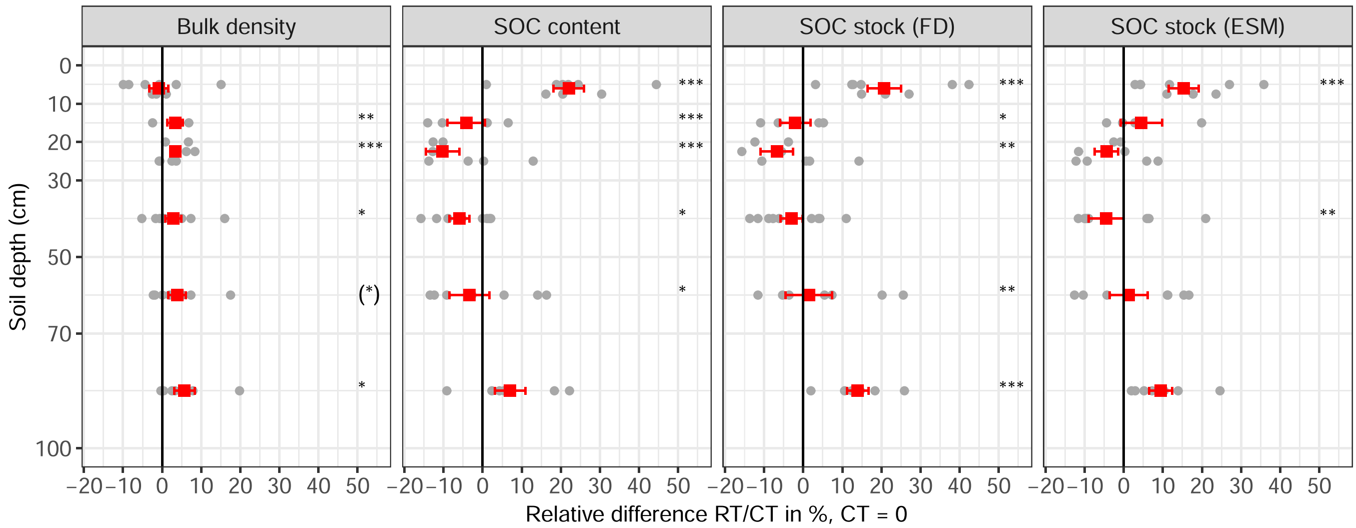

Fig. 2. Relative difference (%) between reduced tillage (RT) and mouldboard ploughing (CT, Zero line) of bulk density (g cm^{-3}), SOC content (g kg^{-1}) and SOC stocks (Mg ha^{-1}) calculated by the fixed depth (FD) and modelled by the equivalent soil mass (ESM) approach in different soil layers after 8–21 years of tillage system differentiation. Dots represent single measurements per site. Squares display the mean relative difference including standard errors per layer. Significance levels: (*) $p < 0.1$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Table 2
Mean (standard deviation) of the relative change (%) and absolute change (Mg ha^{-1}) between reduced tillage (RT) and mouldboard ploughing (CT) regarding cumulative SOC stocks calculated by the fixed depth (FD) and modelled by the equivalent soil mass (ESM) approach across nine field trials after 8–21 years of tillage system differentiation. ANOVA analysis (F-value, significance level) displays tillage system effects. The mean relative sequestration rate is a rough estimate calculated by the division of absolute changes and the respective trial duration. Data per site are displayed in Table S3/S4/S5, Supplement.

			Rel. change	Abs. change	ANOVA			Rel. seq. rate
		N	RT/CT (%)	RT-CT (Mg ha^{-1})	DF	Intercept	Tillage	(Mg ha^{-1} yr^{-1})
Cumulative SOC stocks								
0–30 cm	FD	9	3.92 (7.64)	2.03 (3.95)	96	141.4 ***	18.8 ***	0.16 (0.31)
	ESM	9	4.89 (7.46)	2.37 (3.57)	32	144.8 ***	34.9 ***	0.18 (0.31)
0–50 cm	FD	9	1.74 (5.37)	1.52 (4.15)	96	121.8 ***	3.11(*)	0.09 (0.30)
	ESM	9	1.77 (4.84)	1.35 (3.58)	32	134.5***	87.1 ***	0.07 (0.29)
0–70 cm	FD	8	1.24 (3.99)	1.28 (3.65)	84	69.1 ***	1.65 ns	0.05 (0.28)
	ESM	8	1.98 (4.63)	1.84 (4.38)	28	78.3 ***	1.13 ns	0.09 (0.30)
0–100 cm	FD	7	3.55 (4.34)	3.98 (5.35)	76	39.0 ***	8.61 **	0.27 (0.49)
	ESM	7	3.74 (4.25)	4.11 (5.09)	25	41.2 ***	5.66 *	0.28 (0.44)
Profile distribution of SOC stocks								
0–10/15 cm	FD	9	20.8 (13.2)	3.79 (1.80)	96	90.9 ***	199.2 ***	
	ESM	9	15.4 (11.5)	2.90 (1.78)	33	97.9 ***	174.9 ***	
10 – 20 cm	FD	4	-1.68 (8.34)	-0.38 (1.72)	43	55.8 ***	6.06 *	
	ESM	4	4.50 (10.7)	0.66 (1.62)	15	66.4 ***	0.64 ns	
15/20–30 cm	FD	9	-6.57 (12.5)	-1.59 (2.55)	96	76.5 ***	9.67 **	
	ESM	9	-4.45 (9.01)	-0.83 (1.62)	33	115.6 ***	0.19 ns	
30–50 cm	FD	9	-2.31 (9.03)	-0.51 (1.44)	96	46.5 ***	0.93 ns	
	ESM	9	-4.55 (13.4)	-1.02 (2.62)	33	63.0 ***	12.5 **	
50–70 cm	FD	8	2.03 (16.7)	-0.53 (2.39)	84	20.8 ***	9.71 **	
	ESM	8	1.26 (13.8)	-0.14 (2.26)	29	24.2 ***	0.36 ns	
70–100 cm	FD	7	14.43 (7.4)	2.54 (2.36)	76	13.7 ***	13.2 **	
	ESM	7	9.45 (7.88)	1.76 (2.11)	26	12.6 **	2.48 ns	

Significance levels: ns = not significant, (*)$p < 0.1$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

significantly when modelled with the ESM approach (Table 2). As all sites could be sampled to a soil depth of at least 50 cm, the cumulative SOC stock in 0–50 cm was the most robust with 1.5 (FD) or 1.4 (ESM) Mg ha^{-1} higher stocks in RT than CT and therefore taken for further analysis (e.g. regression with covariables). These SOC stocks represent the relative difference between tillage systems at the time of sampling which ranged between 8 and 21 years after tillage system differentiation. We cannot calculate the real SOC sequestration rate per plot since SOC stocks were not recorded before the trial start. Yet, assuming that the process of SOC stock change is linear and that reduced tillage and ploughed plots in the same trial started at the same SOC level, the relative sequestration rate as the result of the absolute change between RT and CT divided by trial duration accounted for 0.09 (FD) or 0.07 (ESM) Mg ha^{-1} yr^{-1} in 0–50 cm (Table 2, Table S5 Supplement).

3.3. *Tillage effects on crop biomass and soil characteristics*

The average total aboveground biomass was 8% or 1.0 Mg ha^{-1} yr^{-1} lower under RT compared with CT (Table 3). This includes harvested products and e.g. straw residues. The average grass-clover and cover crop biomass produced in the various crop rotations were, however, not significantly different between tillage systems (both −0.04 Mg ha^{-1} yr^{-1}). Crop residue biomass includes all aboveground biomass that was not removed from the field, mainly straw and cover crops. In parallel to

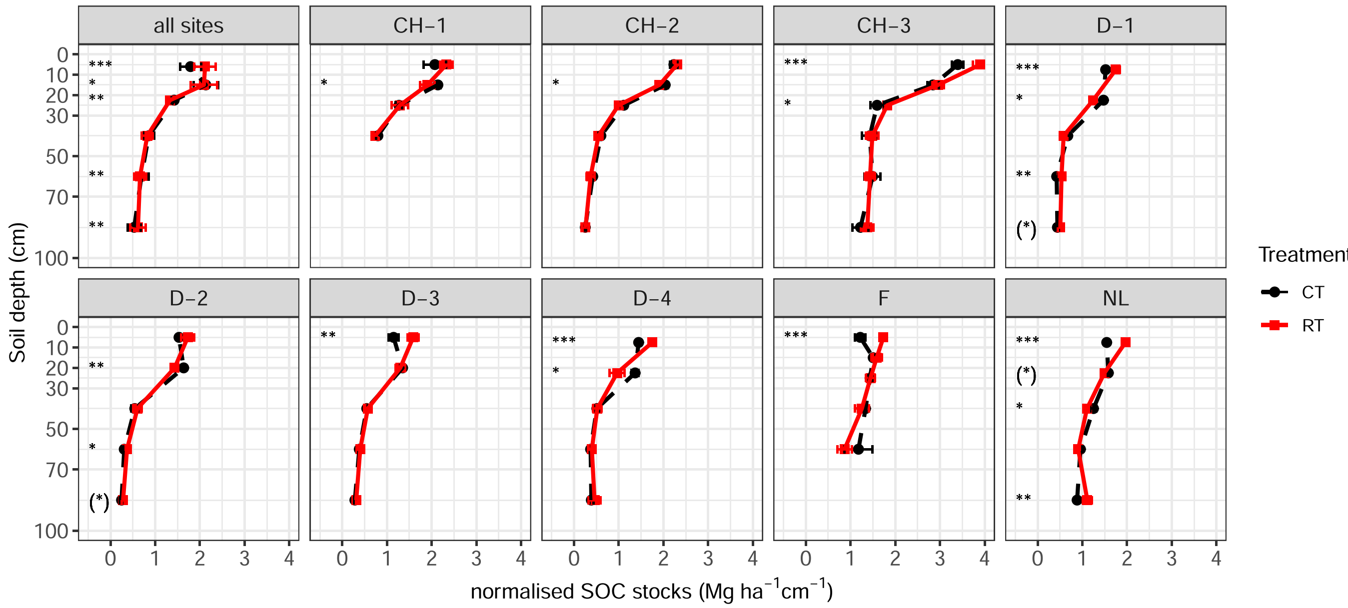

Fig. 3. Profile distribution of absolute SOC stocks (Mg ha^{-1} cm^{-1}) calculated by the fixed depth (FD) approach and normalised by the thickness of the respective soil layer per tillage system (CT = mouldboard ploughing, RT = reduced tillage) of all sites and per site. Symbols are means and error bars represent standard errors. Significance levels: (*)p < 0.1, *p < 0.05, **p < 0.01, ***p < 0.001. Lines are displayed for a better readability (CT = dashed, RT = solid). Absolute and normalised SOC stocks per site and layer can be found in Table S3, Supplement and ANOVA results in Table S4, Supplement.

Table 3
Mean (standard deviation) of the relative change (%) and absolute change between reduced tillage (RT) and mouldboard ploughing (CT) of aboveground biomass (Mg dry matter ha^{-1} yr^{-1}) and aboveground C input (Mg C ha^{-1} yr^{-1}) across nine field trials. ANOVA analysis (F-value, significance level) displays tillage system effects. Data per site are displayed in Table S7, Supplement.

	Relative change RT/CT (%)	Absolute change RT/CT	ANOVA (F-value, significance level)		
			DF	Intercept	Tillage
Average aboveground biomass production (Mg dry matter ha^{-1} yr^{-1})					
Total crop biomass	-7.84 (7.83)	-0.98 (0.94)	32	308.5 ***	17.7 ***
Grass-clover biomass	-0.15 (5.90)	-0.04 (0.22)	26	85.1 ***	3.18 (*)
Cover crop biomass	10.3 (44.4)	-0.04 (0.15)	18	18.1 ***	1.59 ns
Residue biomass return	-5.99 (9.31)	-0.34 (0.49)	32	16.6 ***	40.2 ***
Average aboveground C input (residues , organic fertiliser, Mg C ha^{-1} yr^{-1})					
	-4.81 (7.24)	-0.15 (0.22)	32	43.4 ***	40.2 ***

Significance levels: ns = not significant, (*)p < 0.1, *p < 0.05, **p < 0.01, ***p < 0.001

the total biomass, the average crop residue return was 6% or 0.3 Mg ha^{-1} yr^{-1} lower in RT plots. Crop residue return represented a larger C source with 0.7–5.0 Mg C ha^{-1} yr^{-1} than organic fertilisation with 0–1.4 Mg C ha^{-1} yr^{-1} CT (Table S6, Supplement).

In contrast, weed biomass based on limited data from only five out of nine sites estimated an average of 0.7 Mg ha^{-1} yr^{-1} higher weed biomass or 0.3 Mg C ha^{-1} yr^{-1} higher C input by RT than CT (Table S6, Supplement). The lower C input by residues and fertilisation in RT may have been potentially outbalanced by the higher weed incidence.

Soil texture did not differ between tillage systems across sampled sites, while soil pH was 0.01 pH units significantly higher in RT than CT soils (Table S7, Supplement). On the other hand, sites differed largely with a range of 14–42% in clay content and 5.9–7.2 in soil pH (Table S7, Supplement).

3.4. Pedoclimatic and management effects on SOC stocks

To elucidate which factors impact cumulative SOC stocks (FD) in 0–50 cm between sites, linear regressions based on plot-wise data were calculated (Table 4A). Since the CH-3 site with far highest clay contents and highest SOC stocks dominated the dataset, it was both included and excluded in the analysis. Clay content was only significant when CH-3 was included. Overall, silt content correlated negatively and pH, mean annual precipitation and fertiliser C input correlated positively with SOC stocks. The clay/silt ratio was the best predictor of impacts on SOC stocks (Table 4A, Fig. 4).

The absolute difference between RT and CT (delta RT/CT) per block and site of factors that were significantly affected by the tillage system (Table 3, Table S7) were taken for regression against tillage system changes in SOC stocks (Table 4B). Those factors include soil pH and the aboveground biomass of all crops, grass-clover, cover crops and weeds besides the total C input. None of the factors explained the tillage system change in SOC stocks. Weed and total aboveground biomass with the highest F-values showed a trend towards a positive correlation with SOC stocks. Yet, this was not significant. Delta SOC stocks were also correlated against trial duration, which was also not significant.

4. Discussion

4.1. Depth distribution of SOC stocks as affected by tillage system

Reduced tillage clearly increased topsoil SOC stocks (0–10/15 cm)

Table 4
Linear regressions of A) SOC stocks (0–50 cm) calculated with the fixed depth approach (FD) with pedoclimatic conditions across all sites based on plot-wise data with CH-3 (n = 66) and without CH-3 (*italic*, n = 58) and B) ratio of SOC stocks (0–50 cm) between reduced tillage and mouldboard ploughing (delta RT/CT) with trial duration and the delta RT/CT of total biomass, grass-clover and cover crop and weed biomass and total C input based on block-wise data (n = 33).

	Intercept	Slope	Adj. R^2	DenDF	F-value	sig. level
A) Site comparison: SOC stocks (Mg ha^{-1}) in 0–50 cm						
Clay (%)	32.7	1.59	0.47	64	58.4	***
	71.6	*-0.53*	*0.02*	*56*	*2.00*	*ns*
Silt (%)	101.2	-0.81	0.43	64	49.1	***
	82.0	*-0.47*	*0.38*	*56*	*35.2*	* **
Clay/Silt ratio	49.4	27.2	0.70	64	154.6	***
	41.1	*42.7*	*0.35*	*56*	*31.6*	* **
pH	-10.9	11.7	0.09	64	7.56	**
	2.44	*8.83*	*0.18*	*56*	*13.6*	* *
Mean annual precipitation (mm)	6.99	0.07	0.26	64	23.8	***
	34.3	*0.03*	*0.15*	*56*	*10.8*	* *
Mean annual temperature (°C)	37.8	3.10	0.00	64	1.13	ns
	-15.4	*8.00*	*0.35*	*56*	*32.0*	* **
Total crop biomass (Mg ha^{-1})	115.6	-3.99	0.16	64	13.8	***
	75.3	*-1.12*	*0.02*	*56*	*2.21*	*ns*
Grass-clover biomass (Mg ha^{-1})	69.5	-0.66	-0.01	64	0.15	ns
	68.9	*-2.31*	*0.08*	*56*	*5.71*	*
Cover crop biomass (Mg ha^{-1})	65.0	8.62	0.00	64	1.08	ns
	58.1	*12.3*	*0.09*	*56*	*6.95*	*
Fertiliser C input (Mg C ha^{-1})	56.2	15.4	0.13	64	10.3	**
	53.3	*11.6*	*0.25*	*56*	*19.5*	* **
B) Tillage comparison: Delta RT/CT of SOC stocks in 0–50 cm						
Trial duration	-0.05	0.09	-0.03	31	0.13	ns
Delta RT/CT of pH	1.24	1.61	-0.02	31	0.23	ns
Delta RT/CT of total biomass	2.39	1.18	0.01	31	1.16	ns
Delta RT/CT of grass-clover biomass	1.21	1.40	-0.03	25	0.14	ns
Delta RT/CT of cover crop biomass	2.47	-0.17	-0.06	17	0.00	ns
Delta RT/CT of total aboveground C input	1.29	0.31	-0.03	31	0.00	ns
Delta RT/CT of weed biomass	-2.74	6.67	0.04	17	1.83	ns

Significance levels: ns = not significant, (*)$p < 0.1$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

and decreased SOC stocks in or just below the old plough layer (15/20–50 cm) compared with traditional ploughing. Such a SOC stratification effect can be linked to the lack of mixing of organic matter into deeper soil layers achieved by ploughing (Luo et al., 2010) and is limited to the topsoil in the case of reduced tillage. It may also be related to a change in root growth. Higher root length densities in the topsoil and lower densities in the layers to 30 cm depth compared with ploughing was found across no-till studies globally (Mondal et al., 2019) and for reduced tillage at the French site of our study (Peigné et al., 2018). There, root abundance under reduced tillage was higher in 0–6 cm and lower in 12–70 cm. This root growth effect was attributed to the stratification of nutrients and a change in bulk density (Qin et al., 2006). Higher bulk densities in soil layers lower than 10/15 cm measured in this study confirm a potentially growth limiting factor for roots into subsoil layers. They also suggest that the SOC stock decrease below the upper soil layer and the large SOC stock increase in the upper soil layer despite no change in bulk densities was mainly driven by changes in SOC content.

We found higher SOC stocks in 70–100 cm soil depth across seven sites. Sampling deeper than 70 cm was impossible at two sites (CH-1, F) due to shallow bedrock. Stone and soil carbonate content increased with depth at some sites and, at the NL site, spots of peat were recorded in the subsoil. This introduces more spatial heterogeneity than in upper soil layers, which is known to challenge interpretation (Heinze et al., 2018). Roots and macropores of anecic earthworms may be carbon pathways into deeper soil layers. Yet, root abundance was lower under reduced tillage than under ploughing in lower soil layers at the French site (Peigné et al., 2018) and earthworm monitoring in some of our studied sites did not show an effect of tillage systems on anecic species (Crittenden et al., 2014; Kuntz et al., 2013; Peigné et al., 2018). Whether our observation of higher SOC stocks in 70–100 cm is an effect of spatial heterogeneity or tillage management cannot be answered within this study and offers opportunities for further research.

Overall, the SOC stock profile distribution measured in our study resembles the SOC stock distribution of the well assessed no-till – ploughing comparisons compiled by several meta-analyses, e.g. by Luo et al. (2010) or Ogle et al. (2019). Regarding the topsoil SOC enrichment, it can be assumed that soil erosion control is also achieved by reduced tillage in organic farming, which has been confirmed with direct erosion measurements at the CH-1 site (Seitz et al., 2018).

4.2. *SOC sequestration potential of reduced tillage*

Since conservation tillage systems are discussed as climate change mitigation measures, original studies were repeatedly summarised by meta-analyses. Selecting for ones that also include subsoils, Luo et al.

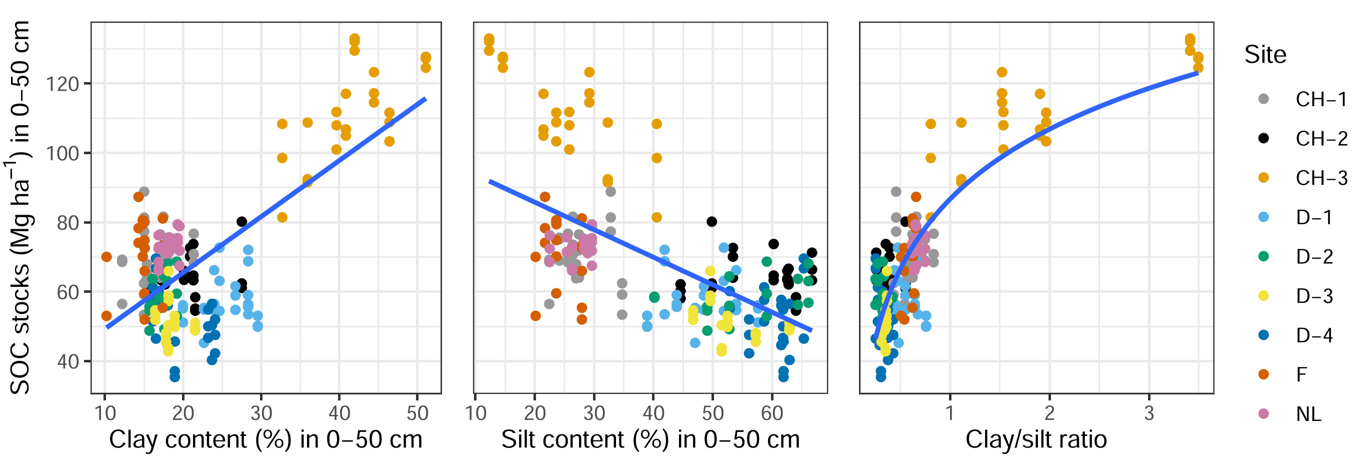

Fig. 4. Regressions of SOC stocks (Mg ha^{-1}) in 0–50 cm calculated by the fixed depth (FD) approach with clay and silt content (%) and the clay-silt ratio across nine field trials.

(2010) reported an insignificant 2.8% (> 40 cm) increase by no-till globally and Meurer et al. (2018) an insignificant increase by 1.2–1.3 Mg C ha^{-1} or 0.1 Mg C ha^{-1} yr^{-1} (0–60 cm) by no-till in temperate climates. Our study, with a total SOC stock increase by reduced tillage of on average 1.7% after 8–21 years, equivalent to 1.5 Mg C ha^{-1} or 0.09 Mg C ha^{-1} yr^{-1} in 0–50 cm shows a similar SOC sequestration for reduced tillage systems in organic farming. A comparison with other reduced tillage studies is more difficult since they mostly did not sample subsoils. For instance, the review of Kämpf et al. (2016) on SOC distribution in topsoils (0–30 cm) in temperate climates indicates that SOC stocks under reduced tillage are intermediate between no-till and ploughing. Blanco-Canqui et al. (2021) sampled two long-term trials in Nebraska (USA) after 34 (0–60 cm) and 39 (0–100 cm) years under climatic conditions similar to our study. While the 39-year-old site showed an increase in total SOC stocks from ploughing to reduced tillage to no-till, SOC stocks at the 34-year-old site were 22% higher under reduced tillage (shallow disc) than ploughing but similar to no-till. In our study after a trial duration of 8–21 years, total SOC stocks in 0–100 cm accounted for 3.6% or 4.0 Mg C ha^{-1} higher SOC stocks with reduced tillage resulting in a far lower increase in SOC stocks than in the study of Blanco-Canqui et al. (2021). We, therefore, confirm that a certain SOC sequestration can be achieved by reduced tillage, even though tillage operations are not entirely stopped. The subsoil SOC processes urgently need further attention in future research. To assess the overall impact of tillage systems regarding climate change mitigation, other aspects like N_2O emissions or fuel consumption need to be considered as well (Guenet et al., 2021; Powlson et al., 2014), since those emissions continue while a SOC steady state is reached after a certain period.

In summary, reduced tillage systems under organic farming conditions can provide some SOC sequestration without the use of herbicides which are of increasing concern (Dang et al., 2015). This is an important outlook regarding future efforts to reduce pesticide inputs in conventional agriculture. Yields are, however, most likely lower than in conservation tillage systems with herbicide use, as indicated in the CH-1 field experiment (Wittwer et al., 2021).

4.3. Drivers of SOC stock changes

Cumulative SOC stocks were overall increased with reduced tillage, suggesting that SOC was enriched or losses reduced. The amount of SOC in soils is regulated by SOC turnover and stabilisation (Chenu et al., 2019) and there is evidence that ploughing disrupts soil aggregates exposing SOC to microbial consumption (Govaerts et al., 2009). Measurements in some of our studied sites support the lower level of soil disturbance in reduced tilled soils. At CH-1, a sandy loam, a change in microbial composition favouring fungi (Hartman et al., 2018; Wagg et al., 2018) in combination with increased aggregate stability (Loaiza Puerta et al., 2018) was determined. Though aggregate stability was similar between tillage systems at CH-3 due to the high clay content (Cania et al., 2020), fungi in general (Kuntz et al., 2013) and arbuscular mycorrhizal fungi that are sensitive to disturbance (Säle et al., 2015) were more abundant in reduced tilled plots.

Tillage systems also impact aboveground carbon input, which was assessed by Virto et al. (2012) who positively related changes in crop C input to SOC stocks (0–30 cm). In our study, regressions of tillage system differences in total crop biomass and weed biomass were slightly but not significantly linked to the SOC stock changes observed. In fact, reduced tillage in the organic farming context of this study decreased crop biomass yields by on average 8% in comparison with ploughing. Such a yield gap was reported by Cooper et al. (2016) and is related to increased weed pressure and plant nutrition issues. This is the main difference to conservation tillage practices in conventional farming, where herbicides and mineral fertilisers can sustain productivity. The decrease in crop biomass in our study led to a 0.2 Mg C ha^{-1} yr^{-1} lower total aboveground C input. The lower input may have been outbalanced by i) higher weed pressure which was estimated to provide 0.3 Mg C ha^{-1} yr^{-1} from aboveground biomass or ii) changes in belowground C inputs, which were not assessed in our study. It should be noted that weed data in this study are based on a limited dataset from four out of nine sites. This is, therefore, only a preliminary comparison that indicates that weeds may be an important source of C input which needs future research.

Interestingly, tillage induced SOC stock changes were not related to trial duration in our study. Therefore, it seems that site-specific pedoclimatic conditions interact with management practices in a more complex way. Trends in SOC stock drivers were more apparent when sites were compared: Soil texture, especially clay contents, is often identified as an important predictor of SOC as fine mineral particles associate with SOC (Wiesmeier et al., 2019). However, in our study, silt content was also well correlated to SOC stocks. The clay/silt ratio finally had the best correlation ($R^2 = 0.7$) and could be a good predictor of SOC stocks, representing the soil texture triangle in a condensed form. Soil pH ranged from 5.9–7.2 across sites. The positive correlation with SOC stocks may hint to the availability of exchangeable cations that were argued to impact SOM stabilisation and clay mineral behaviour (Wiesmeier et al., 2019). Apart from soil parameters, the positive SOC stock correlation with precipitation is commonly found (Wiesmeier et al., 2019). SOC stocks also increased with the amount of organic amendments used (Maillard and Angers, 2014).

4.4. SOC stock assessment

Our study compared SOC stocks that were calculated on a site-specific fixed depth approach with stocks that were further modelled on an equivalent soil mass (ESM). Site specificity means that we considered a priori knowledge on current and historic tillage depths during sampling and that the layers in the Ap horizon thus differ between sites. The equivalent soil mass approach is widely discussed as the more appropriate method as tillage or other soil management practices influence bulk densities and therefore soil masses. There is, however, no standardised protocol of the modelling procedure, and approaches vary considerably (e.g. Ellert and Bettany, 1995; Von Haden et al., 2020; Wendt and Hauser, 2013). In our study, the two approaches yielded the same outcome. As the ESM approach relies on the choice of input variables and the quality of the modelled cubic spline fit, we feel that there are more uncertainties added. Beyond, we have seen, just as Blanco-Canqui et al. (2021), that soil sampling depth has a huge impact when assessing tillage system differences on SOC stocks. This suggests that sampling deep enough is more important than the method used to calculate SOC stocks.

5. Conclusions

Conservation tillage is an important measure to increase soil conservation and is argued to sequester carbon in relation to climate change mitigation. Our study suggests that reduced tillage in organic farming has the potential to sequester SOC in temperate Europe in comparison with ploughing. Since the SOC sequestration is limited in time until a new SOC equilibrium is reached, SOC sequestration by reducing tillage intensity can, however, not replace any efforts to reduce greenhouse gas emissions.

In a pesticide reduction or elimination scenario, reduced tillage in organic farming is an alternative approach to conventional no-till to meet soil conservation goals. Yet, weed regulation and nutrient supply must be improved to obtain a stable and productive cropping system. Strategic tillage may be promising to regulate those issues but needs to be assessed in its impact on SOC stocks in the future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2021.105262.

References

Blanco-Canqui, H., Shapiro, C., Jasa, P., Iqbal, J., 2021. No-till and carbon stocks: Is deep soil sampling necessary? Insights from long-term experiments. Soil. Till. Res. 206, 206.

Bolinder, M.A., Janzen, H.H., Gregorich, E.G., Angers, D.A., VandenBygaart, A.J., 2007. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. Agr. Ecosyst. Environ. 118, 29–42.

Cania, B., Vestergaard, G., Suhadolc, M., Mihelič, R., Krauss, M., Fliessbach, A., Mäder, P., Szumełda, A., Schloter, M., Schulz, S., 2020. Site-specific conditions change the response of bacterial producers of soil structure-stabilizing agents such as exopolysaccharides and lipopolysaccharides to tillage intensity. Front. Microbiol. 11, 11.

Chenu, C., Angers, D.A., Barre, P., Derrien, D., Arrouays, D., Balesdent, J., 2019. Increasing organic stocks in agricultural soils: knowledge gaps and potential innovations. Soil. Till. Res. 188, 41–52.

Cooper, J., Baranski, M., Stewart, G., Nobel-de Lange, M., Bàrberi, P., Fließbach, A., Peigné, J., Berner, A., Brock, C., Casagrande, M., Crowley, O., David, C., De Vliegher, A., Döring, T.F., Dupont, A., Entz, M., Grosse, M., Haase, T., Halde, C., Hammerl, V., Huiting, H., Leithold, G., Messmer, M., Schloter, M., Sukkel, W., van der Heijden, M.G.A., Willekens, K., Wittwer, R., Mäder, P., 2016. Shallow non-inversion tillage in organic farming maintains crop yields and increases soil C stocks: a meta-analysis. Agron. Sus. Dev. 36, 22.

Crittenden, S.J., Eswaramurthy, T., de Goede, R.G.M., Brussaard, L., Pulleman, M.M., 2014. Effect of tillage on earthworms over short- and medium-term in conventional and organic farming. Appl. Soil Ecol. 83, 140–148.

CTIC, 2020. Tillage Type Definitions. Conservation Technology Information Center, accessed 21. April 2020: ⟨https://www.ctic.org/CRM/⟩.

Dang, Y.P., Moody, P.W., Bell, M.J., Seymour, N.P., Dalal, R.C., Freebairn, D.M., Walker, S.R., 2015. Strategic tillage in no-till farming systems in Australia's northern grains-growing regions: II. Implications for agronomy, soil and environment. Soil. Till. Res. 152, 115–123.

EEC, 2013. Council Regulation (EC) No 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No 2092/91.

Ellert, B.H., Bettany, J.R., 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75, 529–538.

Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Mader, P., Stolze, M., Smith, P., Scialabba, N.E.H., Niggli, U., 2012. Enhanced top soil carbon stocks under organic farming. Proc. Natl. Acad. Sci. U.S.A. 109, 18226–18231.

Govaerts, B., Verhulst, N., Castellanos-Navarrete, A., Sayre, K.D., Dixon, J., Dendooven, L., 2009. Conservation agriculture and soil carbon sequestration: between myth and farmer reality. Crit. Rev. Plant Sci. 28, 97–122.

Guenet, B., Gabrielle, B., Chenu, C., Arrouays, D., Balesdent, J., Bernoux, M., Bruni, E., Caliman, J.-P., Cardinael, R., Chen, S., Ciais, P., Desbois, D., Fouche, J., Frank, S., Henault, C., Lugato, E., Naipal, V., Nesme, T., Obersteiner, M., Pellerin, S., Powlson, D.S., Rasse, D.P., Rees, F., Soussana, J.-F., Su, Y., Tian, H., Valin, H., Zhou, F., 2021. Can N2O emissions offset the benefits from soil organic carbon storage? Glob. Chang. Biol. 27, 237–256.

Von Haden, A.C., Yang, W.H., DeLucia, E.H., 2020. Soils' dirty little secret: Depth-based comparisons can be inadequate for quantifying changes in soil organic carbon and other mineral soil properties. Glob. Chang. Biol. 26, 3759–3770. https://doi.org/10.1111/gcb.15124.

Hartman, K., van der Heijden, M.G.A., Wittwer, R.A., Banerjee, S., Walser, J.-C., Schlaeppi, K., 2018. Cropping practices manipulate abundance patterns of root and soil microbiome members paving the way to smart farming. Microbiome 6, 14.

Heinze, S., Ludwig, B., Piepho, H.-P., Mikutta, R., Don, A., Wordell-Dietrich, P., Helfrich, M., Hertel, D., Leuschner, C., Kirfel, K., Kandeler, E., Preusser, S., Guggenberger, G., Leinemann, T., Marschner, B., 2018. Factors controlling the variability of organic matter in the top- and subsoil of a sandy Dystric Cambisol under beech forest. Geoderma 311, 37–44.

Kämpf, I., Hölzel, N., Störrle, M., Broll, G., Kiehl, K., 2016. Potential of temperate agricultural soils for carbon sequestration: a meta-analysis of land-use effects. Sci. Total Environ. 566–567, 428–435.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World Map of the Koeppen-Geiger climate classification updated. Meteorol. Z. 15, 259–263.

Krauss, M., Berner, A., Perrochet, F., Frei, R., Niggli, U., Mäder, P., 2020. Enhanced soil quality with reduced tillage and solid manures in organic farming – a synthesis of 15 years. Sci. Rep. 10, 4403.

Kuntz, M., Berner, A., Gattinger, A., Scholberg, J.M., Mäder, P., Pfiffner, L., 2013. Influence of reduced tillage on earthworm and microbial communities under organic arable farming. Pedobiologia 56, 251–260.

Loaiza Puerta, V., Pujol Pereira, E.I., Wittwer, R., van der Heijden, M., Six, J., 2018. Improvement of soil structure through organic crop management, conservation tillage and grass-clover ley. Soil Tillage Res. 180, 1–9.

Luo, Z.K., Wang, E.L., Sun, O.J., 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agric. Ecosyst. Environ. 139, 224–231.

Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P., Niggli, U., 2002. Soil fertility and biodiversity in organic farming. Science 296, 1694–1697.

Maillard, E., Angers, D.A., 2014. Animal manure application and soil organic carbon stocks: a meta-analysis. Glob. Chang. Biol. 20, 666–679.

Meurer, K.H.E., Haddaway, N.R., Bolinder, M.A., Katterer, T., 2018. Tillage intensity affects total SOC stocks in boreo-temperate regions only in the topsoil-a systematic review using an ESM approach. Earth Sci. Rev. 177, 613–622.

Mondal, S., Chakraborty, D., Bandyopadhyay, K., Aggarwal, P., Rana, D.S., 2019. A global analysis of the impact of zero-tillage on soil physical condition, organic carbon content, and plant root response. Land Degrad. Dev.

Ogle, S.M., Alsaker, C., Baldock, J., Bernoux, M., Breidt, F.J., McConkey, B., Regina, K., Vazquez-Amabile, G.G., 2019. Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. Sci. Rep. 9, 9.

Peigné, J., Vian, J.-F., Payet, V., Saby, N.P.A., 2018. Soil fertility after 10 years of conservation tillage in organic farming. Soil. Till. Res. 175, 194–204.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., R Core Team, 2020. nlme: Linear and Nonlinear Mixed Effects Models, R package version 3.1–147 ed.

Poeplau, C., Don, A., 2015. Carbon sequestration in agricultural soils via cultivation of cover crops - a meta-analysis. Agric. Ecosyst. Environ. 200, 33–41.

Poeplau, C., Vos, C., Don, A., 2017. Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. SOIL 3, 61–66.

Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nat. Clim. Chang. 4, 678–683.

Qin, R.J., Stamp, P., Richner, W., 2006. Impact of tillage on maize rooting in a Cambisol and Luvisol in Switzerland. Soil. Till. Res. 85, 50–61.

R Core team, 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Säle, V., Aguilera, P., Laczko, E., Mäder, P., Berner, A., Zihlmann, U., van der Heijden, M. G.A., Oehl, F., 2015. Impact of conservation tillage and organic farming on the diversity of arbuscular mycorrhizal fungi. Soil Biol. Biochem. 84, 38–52.

Schulz, F., Brock, C., Schmidt, H., Franz, K.-P., Leithold, G., 2014. Development of soil organic matter stocks under different farm types and tillage systems in the Organic Arable Farming Experiment Gladbacherhof. Arch. Agron. Soil Sci. 60, 313–326.

Seitz, S., Goebes, P., Puerta, V.L., Pereira, E.I.P., Wittwer, R., Six, J., van der Heijden, M. G.A., Scholten, T., 2018. Conservation tillage and organic farming reduce soil erosion. Agron. Sust. Dev. 39, 4.

Vandenbygaart, B., Gregorich, E., Angers, D., 2003. Influence of agricultural management on soil organic carbon: a compendium and assessment of Canadian Studies. Can. J. Soil Sci. 83, 363–380.

Vermeulen, S.J., Campbell, B.M., Ingram, J.S.I., 2012. Climate change and food systems. In: Gadgil, A., Liverman, D.M. (Eds.), Annual Review of Environment and Resources, Vol 37. Annual Reviews, Palo Alto, 195-+.

Vian, J.F., Peigné, J., Chaussod, R., Roger-Estrade, J., 2009. Effects of four tillage systems on soil structure and soil microbial biomass in organic farming. Soil Use Manag. 25, 1–10.

Virto, I., Barre, P., Burlot, A., Chenu, C., 2012. Carbon input differences as the main factor explaining the variability in soil organic C storage in no-tilled compared to inversion tilled agrosystems. Biogeochemistry 108, 17–26.

Wagg, C., Dudenhöffer, J.-H., Widmer, F., van der Heijden, M.G.A., 2018. Linking diversity, synchrony and stability in soil microbial communities. Funct. Ecol. 32, 1280–1292.

Walter, K., Don, A., Tiemeyer, B., Freibauer, A., 2016. Determining soil bulk density for carbon stock calculations: a systematic method comparison. Soil Sci. Soc. Am. J. 80, 579–591.

Wendt, J.W., Hauser, S., 2013. An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. Eur. J. Soil Sci. 64, 58–65.

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York.

Wiesmeier, M., Hübner, R., Dechow, R., Maier, H., Spörlein, P., Geuß, U., Hangen, E., Reischl, A., Schilling, B., von Lützow, M., Kögel-Knabner, I., 2014. Estimation of past and recent carbon input by crops into agricultural soils of southeast Germany. Eur. J. Agron. 61, 10–23.

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., von Lützow, M., Marin-Spiotta, E., van Wesemael, B., Rabot, E., Ließ, M., Garcia-Franco, N., 2019. Soil organic carbon storage as a key function of soils-a review of drivers and indicators at various scales. Geoderma 333, 149–162.

Wittwer, R.A., Bender, S.F., Hartman, K., Hydbom, S., Lima, R.A.A., Loaiza, V., Nemecek, T., Oehl, F., Olsson, P.A., Petchey, O., Prechsl, U.E., Schlaeppi, K., Scholten, T., Seitz, S., Six, J., Heijden, M.G.Avd, 2021. Organic and conservation agriculture promote ecosystem multifunctionality. Sci. Adv. 7 eabg6995.

Wittwer, R.A., Dorn, B., Jossi, W., van der Heijden, M.G.A., 2017. Cover crops support ecological intensification of arable cropping systems. Sci. Rep. 7, 7.

Zikeli, S., Gruber, S., 2017. Reduced tillage and no-till in organic farming systems, Germany - status quo, potentials and challenges. Agriculture 7, 35.

Zikeli, S., Gruber, S., Teufel, C.-F., Hartung, K., Claupein, W., 2013. Effects of reduced tillage on crop yield, plant available nutrients and soil organic matter in a 12-year long-term trial under organic management. Sustainability 5, 3876–3894.