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From global trends to local realities: SOC accrual of improved management practices in northwestern Europe

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ABSTRACT

Numerous meta-analyses provide rates of carbon accrual for specific management practices at global scales. However, understanding how specific farming practices and soil properties influence SOC accrual within defined regions remains challenging. We examined whether three well-investigated improved management practices (organic fertilizer input, cover crops, and non-inversion tillage) increase SOC stocks within arable farming in Northwestern Europe. It was hypothesized that SOC accrual would be primarily driven by clay content. We sampled eleven experimental sites, where experimental durations, clay content, and SOC content ranged from 5 to 23 years, 1–20 %, and 0.9–2.3 %, respectively. The sites were sampled according to a uniform protocol for two depths (0–30 and 30–60 cm). Our cross-site analysis revealed substantial variation in SOC responses to the management practices, even within a single climatic region. There was a clear trend of increasing SOC accrual with increasing organic matter inputs from organic amendments, but effects were site dependent. Besides organic amendments, only frost-resistant cover crop species combined with non-inversion tillage accrued SOC at one site. Contrary to our hypothesis, clay content was not the primary driver of SOC accrual. Instead, SOC accrual was most strongly driven by the interplay between experimental duration and the initial SOC stock. Our study underscores the need for context-specific SOC management strategies that account for the initial SOC levels.

1. Introduction

Global food systems are responsible for one-third of global anthropogenic greenhouse gas emissions (Tubiello et al., 2021). N_2O and CH_4 contribute approximately half of the CO_2 equivalents. Global soils represent the largest terrestrial carbon (C) pool and are 154 times larger than annual anthropogenic emissions of CO_2 at the current rate (Friedlingstein et al., 2023). It follows that even minor losses of soil C (a few tenths of a percent) could lead to significantly increased atmospheric CO_2 levels (Paustian et al., 2016). In addition to current emissions, historical agricultural land use and land use change have caused substantial soil carbon losses, leading to the release of about 116 Gt C (425 Gt CO_2 eq.) into the atmosphere (Sanderman et al., 2017). Conversely, a slight increase in global soil organic carbon (SOC) stocks could significantly reduce atmospheric CO_2 levels. This observation has prompted a growing focus on rebuilding SOC stocks in agricultural soils as a climate mitigation strategy (Baveye et al., 2020). The general term that is often used for this process is soil carbon sequestration, which is defined as the removal of carbon from the atmosphere and storage in SOC (Don et al., 2023). Criticism is rising about the role of SOC sequestration in climate mitigation strategies (Amundson and Biardeau, 2018; Moinet et al., 2023; Saifuddin et al., 2024), as well as about CO_2 removal technologies in general (Probst et al., 2024; Schleussner et al., 2024). Nonetheless, losses of SOC are an indicator of soil degradation, much of which is due to inadequate agricultural management practices (Lal, 2004). Identifying farm management practices that maintain SOC stocks or revert SOC losses could help rebuild degraded soils while avoiding additional emissions of GHG.

Much attention has been given to identifying agricultural management practices that support SOC sequestration (Amelung et al., 2020; Minasny et al., 2017). This is particularly the case for soils under arable management, as it has been proposed that they can potentially store more SOC than they do now (Paustian et al., 2016). The scientific community has proposed a multitude of management practices to rebuild SOC stocks in agricultural soils (Lal, 2004; Minasny et al., 2017). Here, we refer to those as "improved" management practices. Many of these practices are used as part of regenerative agriculture (Schreefel et al., 2020), which has principles similar to those of conservation

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agriculture and agroecology, such as utilization of organic fertilizers, maximal soil cover, minimal soil disturbance, and diversification of crop rotations (Kassam et al., 2018).

There is substantial literature on the effects of improved management practices on SOC stocks from long-term field experiments globally. Numerous reviews and meta-analyses report SOC sequestration rates (Bolinder et al., 2020; Lessmann et al., 2022; Tiefenbacher et al., 2021). Here, following the recommendation from Don et al. (2023), we make an explicit distinction between SOC sequestration (an increase in SOC stocks over time) and SOC accrual (an increase in SOC stocks as compared to a reference plot with no improved management practice applied). Actual SOC sequestration can most easily be inferred from time series measurements or when the steady-state assumption (constant SOC stock over time) can be verified in the reference treatments, but most studies referring to SOC sequestration provide estimates of SOC accrual (Don et al., 2023).

While informative as a general estimate on a global scale, yearly SOC accrual rates provided in meta-analyses often fall short of considering the importance of local context. Clay content is frequently cited as a crucial driver of context-specific SOC accrual because the mineral surfaces of clay particles can bind organic matter (Wiesmeier et al., 2019). Recent studies also suggest that both clay and initial SOC stocks can play a critical role in determining SOC accrual (Muleke et al., 2023). The level of carbon inputs to the soil, and ultimately net primary productivity, also appears key in defining accrual rates (Janzen et al., 2022; Poeplau et al., 2024). The duration of the experiment or the time since conversion to improved practices is also critical, albeit sometimes poorly or not reported, because rates of sequestration and accrual decrease over time (Moinet et al., 2023). The specificity of the effects of improved management practices to different pedoclimatic contexts is recognised, but there remain significant gaps in understanding the mechanisms regulating accrual across practices (Amelung et al., 2020).

Recognising this gap, Lessmann et al. (2022) derived SOC accrual rates of arable management practices for different climatic regions across the globe. Considering the climatic context, they multiplied the rates with spatially explicit data about the potential area for adopting such practices to estimate carbon accrual potentials in arable land. Soil property variations within a climatic region were not considered in the study, due to upscaling issues. Still, the authors stated that this might have overestimated the accrual potential of the management practices assessed. A more recent study by Gocke et al. (2023) addressed this limitation by investigating SOC accrual rates of different management practices across various arable sites in Germany. They found that SOC stock changes showed substantial variation within a single country. These findings underline the need for more context-specific assessments of SOC accrual that account for regional variability.

Here, we focus on the region of Northwestern Europe. We evaluated the SOC accrual of three management practices: 1) organic fertilizer (primarily compost), 2) non-inversion tillage (NIT), and 3) cover crops, at a range of experimental sites across different soil types. SOC accrual was estimated using standard management practices such as synthetic fertilizer, conventional tillage, and no cover crops as references. Our objectives were twofold: i) provide locally relevant estimates of accrual rates for the three above-mentioned improved management, and ii) improve understanding of the drivers and limitations to SOC accrual. We hypothesized that SOC accrual rates of the management practices would vary across sites and depend on the initial soil properties, with clay content being the most crucial driver.

2. Materials and methods

2.1. Site description

We selected eleven experimental sites across Northwestern Europe, focusing on areas with varied arable management practices and spanning a range of soil textures from sandy to loamy (Fig. 1, Table 1), situated within the temperate Cfb Köppen-Geiger classification (Beck et al., 2018). This region is characterized by, on average, high SOC stocks (Lugato et al., 2014) and intensive agricultural production systems (Giannakis and Bruggeman, 2018). A detailed description of the sites can be found in the supplementary material (supplementary site description and Table S1). The selection criteria were designed to capture the diversity in soil conditions and improved management practices prevalent in the region. These practices were selected based on their prominence in regenerative agriculture, applied soil research in the region, and their potential for SOC accrual. Each site was chosen based on its potential to provide insights into the effects of soil texture and initial SOC stocks on SOC accrual, emphasizing long-term field experiments that had been operational for at least five years. The sites span a diverse range of experimental durations (5–23 years), clay contents (1–20 %),

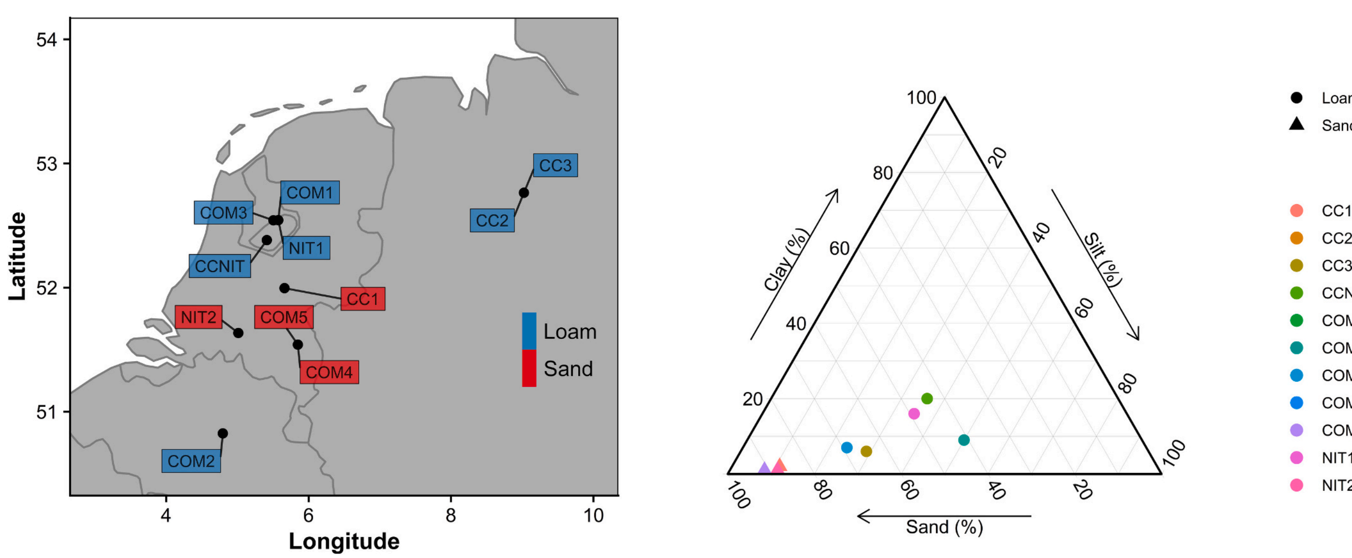

Fig. 1. Map of the field experiments investigated in Northwestern Europe for effects of improved management practices on SOC stocks on sandy soil (red) and loam soil (blue). CC1 = Nergena Cover Crops experiment, CC2 = Cover crops Asendorf experiment, CC3 = Cover crops Asendorf experiment, CCNIT1 = Maize Flevoland experiment, COM1 = BASIS compost experiment, COM2 = Soil Service of Belgium Compost experiment, COM3 = Manure as an opportunity experiment, COM4 = Vredepeel organic matter experiment 1, COM5 = Vredepeel organic matter experiment 2, NIT1 = BASIS tillage experiment, NIT2 = Maize Brabant experiment.

Table 1
Characteristics of each site used to evaluate the effects of improved management practices on SOC stocks. pH, texture and SOC are given for the topsoil (0–30 cm) in the reference.

Sites	Field trail name	Evaluated practices	Treatments	GPS, country	Trial start	Duration (years)	Crop rotation[1]	pH	Texture	SOC stock and content	Literature
COM1	BASIS compost experiment	Organic fertilizer	NPK and different amounts of green compost (0, 1.6, 3.2 t C)	52°36′ N, 5°48′ E (NL)	2011	11	PE, BA, SB, PO, UN, WW, PO	7.6	Loam, 16 % clay, 35 % silt	39 t C ha^{-1}, 0.9 %	Balen et al. (2023)
COM2	Soil Service of Belgium Compost experiment	Organic fertilizer	NPK and different amounts of vegetable, fruit, and garden (VFG) compost[2] (0, 1.6, 3.2, 4.8 t C)	50°49′N, 4°47′E (BEL)	1997	23	PO, SB, SB, WW	6.6	Loam, 9 % clay, 50 % silt	40 t C ha^{-1}, 0.9 %	Tits et al. (2014)
COM3	Manure as an opportunity experiment	Organic fertilizer	NPK and different organic fertilizers: 0.7 t C slurry, 0.8 t C chicken manure, 2.3 t C FYM, 0.7 t C VFG-compost, 0.7 t C slurry + VGF-compost, 2.7C t nature-compost	52.32° N, 5.30° E (NL)	1999	21	SAL, LE, MA, PA, BA, SPO, JER	7.4	Loam, 7 % clay, 24 % silt	39 t C ha^{-1}, 0.9 %	Bakker et al. (2020)
COM4	Vredepeel organic matter experiment 1	Organic fertilizer	NPK and 1.4 t C green-compost without slurry	51°32′N, 5°51′E (NL)	2011	8	PO, PE, LE, BA, CAR, MA	5.7	Sand, 1 % clay, 8 % silt	105 t C ha^{-1}, 2.3 %	de Haan et al. (2018)
COM5	Vredepeel organic matter experiment 2	Organic fertilizer	NPK and 1.4 t C green compost with slurry	51°32′N, 5°51′E (NL)	2011	8	PO, PE, LE, BA, CAR, MA	5.7	Sand, 1 % clay, 8 % silt	100 t C ha^{-1}, 2.3 %	de Haan et al. (2018)
NIT1	BASIS tillage experiment	Non-inversion tillage	Standard tillage and non-inversion tillage	52°36′ N, 5°48′ E (NL)	2009	11	PE, BA, SB, PO, UN, WW, PO	7.6	Loam, 16 % clay, 35 % silt	43 t C ha^{-1}, 0.9 %	Balen et al. (2023)
NIT2	Maize Brabant experiment	Non-inversion tillage – maize	Standard tillage and non-inversion tillage	51° 37′N, 5° 0′E (NL)	2012	7	MA, WW	5.0	Sand, 1 % clay, 11 % silt	86 t C ha^{-1}, 2.1 %	(Sleiderink et al., 2024)
CCNIT1	Maize Flevoland experiment	Non-inversion tillage, Cover crops	Standard tillage and non-inversion tillage and cover crops (fallow, grass, rye, rye + pea)	52° 31′N, 5° 33′E (NL)	2009	14	MA	7.6	Loam, 20 % clay, 36 % silt	58 t C ha^{-1}, 1.4 %	Stienezen et al. (2020)
CC1	Nergena Cover Crops experiment	Cover crops	Cover crops (fallow, Japanese oats, radish, Japanese oats + Radish, Japanese oats + radish + vetch)	51°59′N, 5°39′E (NL)	2016	5	PO, BA, PE, MA, WW	5.2	Sand, 2 % clay, 11 % silt	53 t C ha^{-1}, 1.2 %	Elhakeem et al. (2023)
CC2	Cover crops Asendorf experiment 1	Cover crops	Cover crops (Fallow, Mustard, mix of 4 species, mix of 12 species) with Faba bean in rotation	52°45′N, 9°01′E (GER)	2016	6	MA, WW, FB	5.8	Loam, 6 % clay, 29 % silt	53 t C ha^{-1}, 1.4 %	Gentsch et al. (2023)
CC3	Cover crops Asendorf experiment 2	Cover crops	Cover crops (Fallow, Mustard, mix of 4 species, mix of 12 species) without Faba bean in rotation	52°45′N, 9°01′E (GER)	2016	6	MA, WW	5.8	Loam, 6 % clay, 29 % silt	64 t C ha^{-1}, 1.4 %	Gentsch et al. (2023)

[1] PO –potato, SB – sugar beet, ON – onion, WW – winter wheat, CC – winter cover crop, GRS – grass seed, MA – maize, CAR – carrot, PE – Peas, LE – leek, BA –barley, HE – hemp, SAL – salsify, PA – parsnip, SPO - sweet potato, JER – Jerusalem artichoke, GRC – grass-clover, CAB – cabbage, FB – faba bean.
[2] Vegetable, fruit, and garden (VFG) compost is composed of municipal waste, nature-compost is composed of plant cuttings from natural areas, green-compost is composed of road-side cuttings with wood and grass.

and SOC contents (0.9–2.3 %) (Table 1) but are located within a relatively small area (1.05 10^{11} m^2). We grouped the studied sites based on the main improved management practices tested: organic fertilizer use (primarily compost) (COM), cover crops (CC), and non-inversion tillage (NIT). For each management practice, we compare SOC stocks between treated plots and reference treatments, using the reference SOC stocks as a proxy for initial SOC stocks. This comparison aims to isolate the effects of management practices on SOC accrual, considering the influence of soil texture and initial SOC levels.

Five sites with compost additions were sampled (COM1, COM2, COM3, COM4, COM5), and one site additionally included different types of animal manure (COM3). COM4 and COM5 were both located at the Vredepeel exp. site, but in COM4, compost effects were evaluated without slurry, whereas in COM5, slurry was applied to both treatments. Soil tillage (e.g., conventional versus non-inversion tillage (NIT)) was investigated at two sites (NIT1, NIT2) and in a combined tillage and cover crop experiment (CCNIT1). Cover crops in monocultures and mixtures were evaluated in CC1, CC2, CC3, and CCNIT1. The cover crops at all sites were grown between two cash crops. CC2 and CC3 were both located at the Asendorf, Germany exp. site but had a distinct crop rotation with maize and wheat and faba bean at CC2 and maize and wheat at CC3. We treated COM4 and COM5 (located at Vredepeel exp. site) and CC2 and CC3 (located at Asendorf exp. site) as separate sites. Further details about the sites and treatments are available in the Supplementary material (Table S2). The reference treatments varied slightly between experiments because they were designed to be control treatments within each experimental site, but all reference treatments were managed under *Good Agricultural Practice*. All reference treatments received regular ploughing, except for the CC2 and CC3 sites, where NIT was applied. All treatments received mineral fertilization, except for slurry in the CCNIT, NIT2, and COM4 and COM5 sites. On most sites, cover crops were applied, and they were also included in the reference treatments. Reference treatments were fallow only in the cover crop experimental sites (CC1, CC2, CC3, CCNIT1). We divided the sites into the main soil types of sand and loam, based on their textural composition (Fig. 1).

2.2. Soil sampling and measurements

Soil sampling was conducted in autumn (between October and December) from 2018 to 2022. A standardized procedure, adapted from Fernandez et al. (2017) was used to ensure consistency across sites. The sampling focused on two soil depth layers (0–30 cm and 30–60 cm) to capture potential differences in SOC accrual within the soil profile. In each plot, 40 soil samples were randomly taken within a rectangle of 2 by 3 m in the middle of the plot using a soil gauge (∅ 1 cm) to a depth of 60 cm. We divided each soil core into two layers: 0–30 cm and 30–60 cm. All crops and grass residues were removed, and the soil cores per depth layer were combined to make a single composite sample for the plot. In the laboratory, samples were sieved through a 2 mm mesh and homogenized. Soil organic carbon (SOC), soil organic matter (SOM), clay content, and pH were analysed for each sample, with particular attention given to the methodological consistency across different soil types and depths. For SOC, dry soil was incinerated at 1150 °C, and the produced CO_2 was determined by an infrared detector (LECO Corporation, St. Joseph, Michigan, USA) (NEN-ISO 10694). SOM was determined by the mass loss upon ignition of the soil at 550 °C after drying at 105 °C (NEN 5754), as based on Ball (1964). The pH was measured in a soil solution with 0.01 M $CaCl_2$ (NEN-EN-ISO 10390). Soil texture was determined with near-infrared spectroscopy (NIRS) (Reijneveld et al., 2022). Before using the pipette method for particle size distribution (NEN 5753) as the reference method, soil organic carbon (SOC), carbonates, and iron were removed. We dug one profile pit measuring 50x50x60 cm to determine the soil bulk density. Bulk density rings with a volume of 0.1 dm^3 were carefully hammered into the soil along the side of the pit at a depth of 15 cm and 45 cm beneath the soil surface, then carefully removed without disturbing the soil within the ring. At each depth, three bulk density samples were taken. Samples were weighed, oven-dried at 70 °C for 48 h, and reweighed to calculate the soil bulk density.

2.3. Calculations

The bulk density *Bd* (kg $dm^{3-\ 1}$) was calculated according to eq. 1:

$$Bd = \frac{Soil\ mass}{Ring\ volume} \tag{1}$$

where the *Soil mass* (kg) represent the dry weight of the soil within a *Ring volume* of 0.1 dm^3.

For each soil depth layer (0–30 cm, 30–60 cm, and 0–60 cm), we calculated SOC stocks (SOC_{stock}) using the equivalent soil mass (ESM) approach (Wendt and Hauser, 2013). The ESM approach accounts for changes in *Bd* within different treatments. This approach expresses the SOC_{stock} in terms of the mineral soil mass (kg ha^{-1}). The $Mass_{mineral\ soil}$ is calculated according to eq. 2.

$$Mass_{mineral\ soil} = (Bd^{*}depth^{*}10000) - (SOM_{content}{}^{*}Bd^{*}depth^{*}10000) \tag{2}$$

where *Bd* is the bulk density (kg dm^{-3}), $SOM_{content}$ represents the soil organic matter (SOM) content of fine soil particles (<2 mm) in mass percentage and the *depth* is an interval (m) multiplied by the area of a hectare in (m^2).

To calculate the SOC_{stock} (kg ha^{-1}), the $Mass_{mineral\ soil,mean\ site}$ within the 0–30 cm or 30–60 cm depth intervals from all plots within a respective site served as the scale basis, in line with Gocke et al. (2023), according to eq. 3:

$$SOC_{stock} = SOC_{content}{}^{*}Mass_{mineral\ soil,\ mean\ site} \tag{3}$$

where $SOC_{content}$ represents the SOC content of fine soil particles (<2 mm) in mass percentage. The SOC stock in the 0–60 cm soil depth layer was calculated according to eq. 4:

$$SOC_{stock\ 0-60cm} = SOC_{stock\ 0-30cm} + SOC_{stock\ 30-60\ cm} \tag{4}$$

SOC accrual (t ha^{-1}), the change in SOC stock attributed to improved management practices compared to a reference treatment, was calculated per soil depth layer according to eq. 5:

$$SOC\ accrual = SOC_{stockM} - SOC_{stockR} \tag{5}$$

where *SOC accrual* (t ha^{-1}) is the difference in the SOC_{stockM}in the improved management practice treatment and the SOC_{stockR} in the reference.

SOC accrual is defined as an increase in SOC stock at a given unit of land, starting from an initial SOC stock or compared to a reference (Don et al., 2023). This does not necessarily result in SOC sequestration in a soil, because other external factors, such as climate change, might cause a decline in both treatments, wherein a positive SOC accrual indicates a reduction of SOC losses. We chose this approach, similar to that proposed by Gocke et al. (2023), because initial SOC stocks were not available in all sites, different soil depth layers were sampled in the past across sites or different analytical procedures were used.

The $SOC_{accrual\ rate}$ (t C ha^{-1} yr^{-1}) was calculated according to eq. 6:

$$SOC_{accrual\ rate} = \frac{SOC_{stockM} - SOC_{stockC}}{Duration} \tag{6}$$

where the *Duration* (years) is the difference between the starting year of the experiment and the sampling year. We are aware that this assumes a linear change of SOC stocks over time, whereas SOC stock change follows a flattening curve into a new steady-state between carbon inputs and decomposition (Poulton et al., 2018). The point at which a new steady state is developing is highly uncertain and depends on, for example, soil properties and historic land use. On the other hand, in cases of high SOC stocks, management practices may not lead to a further increase due to patterns of saturation (Stewart et al., 2007). In addition, calculating the SOC accrual rate enables us to compare our results with *meta*-analyses.

2.4. Statistical analyses

All statistical analyses were performed with R (R Development Core Team, 2013), version R-4.3.1. The SOC accrual was first tested for deviations from 0 for each treatment per site with a one-sample *t*-test. This was done per soil depth layer (0–30 cm and 30–60 cm) and in the full soil depth layer (0–60 cm), together with a visual inspection of a deviation from normality.

A multiple regression analysis was conducted to identify the main drivers of SOC accrual, including experimental duration, reference SOC stock, clay content and management practices (cover crops, organic fertilizer input and tillage) (eq. 7). The analysis incorporated a mixed-effects model to account for site-specific variability, ensuring that the findings are robust and reflective of the diverse conditions across Northwestern Europe. Special attention was given to the interaction between initial SOC stocks and experimental duration, as well as the potential for statistical artifacts in the relationship between initial SOC stocks and SOC accrual. We used the protocol of Zuur and Ieno (2016) to develop our statistical procedure. The management variables expressed the difference within a site between an improved management practice treatment and the reference treatment (Table S1). We calculated the organic fertilizer input as compared to the reference treatment of different organic fertilizer types (compost, animal manure) by converting the inputs using their carbon content as described in the official Dutch fertilization recommendations (Hanegraaf et al., 2021). Reference treatments were dropped from the overall analyses across sites (eq. 7) because SOC accrual was calculated based on these treatments. In addition, the treatment with no fertilization at COM2 was removed as this was not a management practice investigated in this study. In some cases, we missed data for the pH in the subsoil due to technical problems, which were therefore not included in statistical analyses of the subsoil.

A correlation plot was made using Pearson correlations between numerical variables and point-biserial correlations between the categorical variables (tillage and cover crops) and numerical variables (Kornbrot, 2014). Variance Inflation Factor (VIF) scores were determined to check for multicollinearity between single variables. Due to strong collinearity (VIF > 4) between the *Clay* and *pH*, the *pH* was dropped from the multiple regression model. We performed a backward model selection based on the AIC criterion. Model assumptions were checked with diagnostic plots and a Shapiro test of the residuals. SOC accrual did not show normality of residuals (Fig. S4), especially in the full soil depth layer. Still, we wanted to pursue absolute values of SOC accrual instead of relative changes, such as response ratios, because they can be more sensitive to statistical artifacts (Slessarev et al., 2023). We performed linear mixed models with the site as a random factor. Due to a high correlation between pH and clay content across sites (see results and Fig. 3), only clay was included in the models. The full initial models are described in eq. 7:

$$SOC\ accrual \sim Duration + SOCstock_R + Clay + Cover\ crops + Organic\ fertilizer + Tillage + SOCstock_R : Duration + Random(site) \tag{7}$$

Where *Duration* is the experimental duration (years), $SOCstock_R$ is the SOC stock in the reference treatment (t ha^{-1}), *Clay* is the percentage of clay (%), *Cover crops* indicates whether a treatment had a cover crop (cover crops/fallow), *Organic fertilizer* indicates the amount of applied organic fertilizer carbon (t C ha^{-1} year^{-1}) and *Tillage* indicates whether there was non-inversion tillage or conventional tillage. The model was performed for all soil depth layers (0–30 cm, 30–60 cm, and 0–60 cm).

3. Results

3.1. Initial soil properties across sites and practices

The SOC stocks in the reference treatments across eleven field experiments showed considerable variability and were significantly correlated with the clay content (Fig. 2). The SOC stocks ranged from 35 to 127 t C ha^{-1} in the topsoil (0–30 cm) and from 13 to 99 t C ha^{-1} in the subsoil (30–60 cm). The variability differed with primary soil type, with SOC stocks in sandy soils ranging between 43 and 122 t C ha^{-1} within the topsoil layer, whereas loamy soils showed a narrower range of 37–66 t C ha^{-1}.

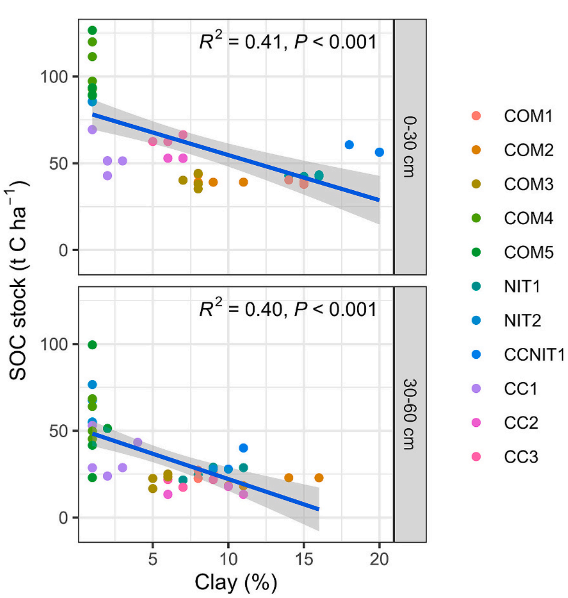

Fig. 2. SOC stocks (t C ha^{-1}) in the reference treatments related to clay content (%) across all sites in the topsoil (0–30 cm) and subsoil (30–60 cm). Standard management practices were applied in the reference treatments.

Correlations were found between management practices and environmental variables, suggesting significant interactions (Fig. 3). For instance, reference SOC stocks positively correlated with pH and experimental duration. However, it is essential to note that the correlation coefficients did not exceed a threshold of 0.6 except for the relationship between clay content and pH.

3.2. Improved practices and SOC accrual

The effect of the improved management practices on SOC accrual rates (Fig. 4) and absolute SOC accrual over the experimental period (Fig. 5) varied significantly depending on the specific conditions of each site. Organic fertilizer treatments with compost exhibited the most consistent positive SOC accrual rates, although this was not significant at all sites. The SOC accrual rates from animal manure addition were also positive but insignificant. The effects of NIT and cover crops on SOC accrual showed a wide range across different sites. Only the combination of NIT with a cover crop species mixture led to SOC accrual over 14 years at one loam site. At some sites, significant SOC accrual was also observed in the subsoil.

3.2.1. Organic fertilizers

Organic fertilizer treatments with compost exhibited increases in SOC stocks at two of the three loam soil sites (in COM1, COM2, but not in COM3) compared to mineral-fertilized references. At the sandy soil sites (COM4 and COM5), no carbon accrual was observed (Fig. 5). At the loam soil site, COM2 in Belgium, all vegetable, fruit, and garden waste (VFG) compost additions led to SOC accrual across all soil depths. Additions of 1.6, 3.2, and 4.8 t C ha^{-1} yr^{-1} resulted in SOC accrual of 26, 38, and 56 t C ha^{-1} in the full soil depth layer of 0–60 cm over 23 years, respectively, as compared to the reference SOC stock of 61 t C ha^{-1} (Fig. 5). This translated to a SOC accrual rate between 1.1 and 2.5 t C ha^{-1} yr^{-1} in the full depth layer (Fig. 4). The treatment receiving no fertilization lost 7.7 t C ha^{-1} relative to the mineral fertilized reference in the topsoil (Fig. 5). At COM1, the highest annual green compost additions of 3.2 t C ha^{-1} increased SOC stocks with 10 t C ha^{-1} in the full soil depth layer (0–60 cm) (Fig. 5), equivalent to a SOC accrual rate of 1.1 t C ha^{-1} yr^{-1} (Fig. 5). At the third COM3 site on loam soil, none of the treatments with either compost or animal manure, accrued carbon over 21 years (Fig. 4). We calculated the amount of carbon applied through organic fertilizers at all sites and treatments. From the treatments that show carbon accrual ($P < 0.05$), we observed a SOC accrual rate ranging between 1.1 and 2.5 t C ha^{-1} yr^{-1} and between 0.3 and 0.6 t C per t applied compost C ha^{-1} yr^{-1} in the full soil depth layer.

3.2.2. Non-inversion tillage and cover crops

The effects of non-inversion tillage (NIT) and cover crops on SOC accrual presented varied outcomes across different soil sites (Fig. 4). At the site with a loam soil (NIT1), NIT did not change SOC stocks in any soil depth layer when compared to ploughing (Fig. 5). Conversely, at the sandy soil site (NIT2) with continuous maize cultivation following grassland, NIT led to a SOC accrual of 8.5 t C ha^{-1} (Fig. 5), translating to an accrual rate of 1.2 t C ha^{-1} yr^{-1} (Fig. 4), attributed to a change in the subsoil. At site CCNIT1, again on loam soil, where continuous maize cultivation was applied following grassland, there was no SOC accrual because of NIT or cover crops alone (Fig. 5). However, the combination of NIT with a cover crop species mixture of rye and pea led to an accrual in SOC of 12 t C ha^{-1} over 14 years in the full soil depth layer, equating to a rate of 0.9 t C ha^{-1} yr^{-1} (Fig. 4). This specific combination outperformed all other cover crop treatments at CCNIT1, which did not

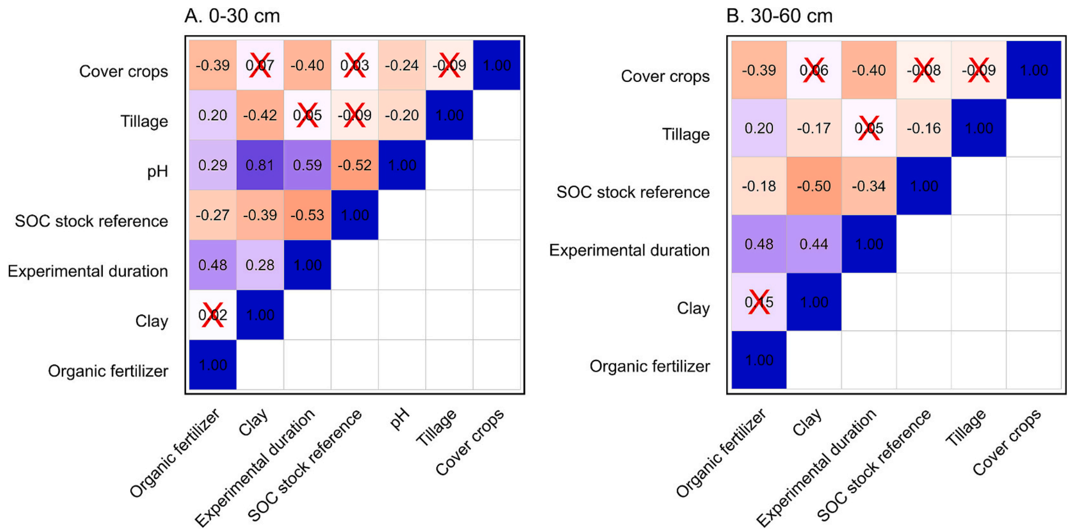

Fig. 3. Correlation plots for A) the topsoil (0–30 cm) and B) the subsoil (30-60 cm) for all sites and treatments. A cross indicates a relationship with a $P > 0.05$. Blue indicates positive and red negative correlations. Pearson correlations were used for continuous variables; point-biserial correlations were used between categorical variables (tillage and cover crops) and continuous variables.

yield SOC stock increases. In another experiment in Germany on loam soil (CC2 and CC3), and at the sandy soil site (CC1), no SOC accrual was observed for any of the cover crop treatments (Fig. 5).

3.3. Drivers of SOC accrual across sites

We used a multiple regression analysis to identify key drivers of SOC accrual across soil depth layers and sites (Eq. 7). This analysis revealed that in the topsoil (0–30 cm), SOC accrual was positively correlated with organic fertilizer input, the adoption of non-inversion tillage, and the experimental duration (Fig. 6A-C, Table S3) (marginal $R^2 = 0.51$). In addition, in the topsoil, we detected a significant interaction between the reference SOC stock and the duration of the experiment, indicating greater accrual over longer durations in soils with lower initial SOC stocks compared to those with higher initial stocks. The model output suggested an inflection point of 54 t C ha^{-1} in the reference plots below which the positive relationship between duration and accrual becomes negative (keeping other variables constant in the model: organic fertilizer of 0.8 t C ha $^{-1}$ year^{-1} and conventional tillage).

In the subsoil layer (30–60 cm), we observed a significant negative relationship between SOC accrual and the reference SOC stock (Fig. 6D, Table S3, marginal $R^2 = 0.18$), where SOC accrual became negative with a reference SOC stock of approximately 40 t C ha^{-1}. There was no significant interaction between reference SOC stock and experimental duration.

Within the full soil depth layer (0–60 cm), the following relationships were observed: organic fertilizer inputs positively influenced SOC accrual, and higher reference SOC stocks were linked to lower accrual rates (Fig. 6E-F, Table S3, marginal $R^2 = 0.27$), where SOC accrual became negative with a mean reference SOC stock of approximately 125 t C ha^{-1}, keeping the other variable constant in the model: organic fertilizer of 0.8 t C ha^{-1} year^{-1}. Neither cover crops nor clay content (1–20 %) significantly affected SOC accrual in any analysed soil layer, and the experiment duration was not discerned as a driver of SOC accrual in the subsoil or the full soil depth layer.

4. Discussion

4.1. Clay content versus initial SOC stocks

Contrary to our hypothesis, clay content was not the primary driver of SOC accrual within our study region. Instead, the interplay between SOC stock of reference treatments (used as a proxy for initial SOC stocks) and the experimental duration was the main factor explaining SOC accrual for the 0-30 cm layer. Empirical studies typically show a positive relationship between SOC accrual and clay content (e.g. Gocke et al., 2023; Gross and Glaser, 2021). Therefore, it remains surprising that clay content (1–20 %) did not emerge as the primary driver of SOC accrual in our context. We observed an unusual negative relationship between clay content and reference SOC stocks (Fig. 2) across the sites on our arable mineral soils. This is an unusual relationship, as the highest SOC stocks are usually found on soils with a higher clay content (Wiesmeier et al., 2019). However, recent findings by Begill et al. (2023) underscore that coarse soils have a higher capacity for organic carbon storage in their fine fraction than previously thought. This finding highlights the limitations of clay content alone in explaining SOC accrual potential. Notably, high SOC stocks were observed in sandy soils at sites COM4 and COM5. These elevated SOC levels at COM4 and COM5 are likely attributable to historical land-use changes, where natural peat vegetation was cleared to cultivate sandy soils (Pape, 1970). This underscores the critical role of the land-use legacy in shaping SOC stocks, which in turn modulates the effect of current management practices on SOC accrual.

Gocke et al. (2023) observed the highest SOC accrual in sandy soils, but these soils also had the lowest reference SOC stocks (∼20 t C ha^{-1}). This is partly in line with our observation that the greatest SOC accrual occurred where reference SOC stocks were lowest (loamy soils). The existence of a correlation between clay content and initial SOC stocks across sites (negative in our case, and positive in the case of Gocke et al., 2023) may make it difficult to separate the effect of clay from that of initial SOC. However, our correlation analysis and checks of multicollinearity thresholds on our model allowed us to conclude with reasonable confidence that initial SOC stocks, rather than clay, were the primary determinant at our sites. Our findings suggest that soils with initially high SOC stocks tend to adjust naturally towards a lower steady-state level over time. In contrast, those with lower initial stocks demonstrate greater potential for SOC accrual, which may overrule texture's effect on SOC stabilisation.

Recent empirical studies (De Rosa et al., 2024; Georgiou et al., 2022; Gocke et al., 2023; Gross and Glaser, 2021) reappraise the critical role of initial SOC levels driving the site-specificity of SOC accrual. Furthermore, modelling studies corroborate empirical findings, demonstrating that SOC accrual rates diminish when initial SOC stocks are already high (Muleke et al., 2023), with significant consequences for global soil

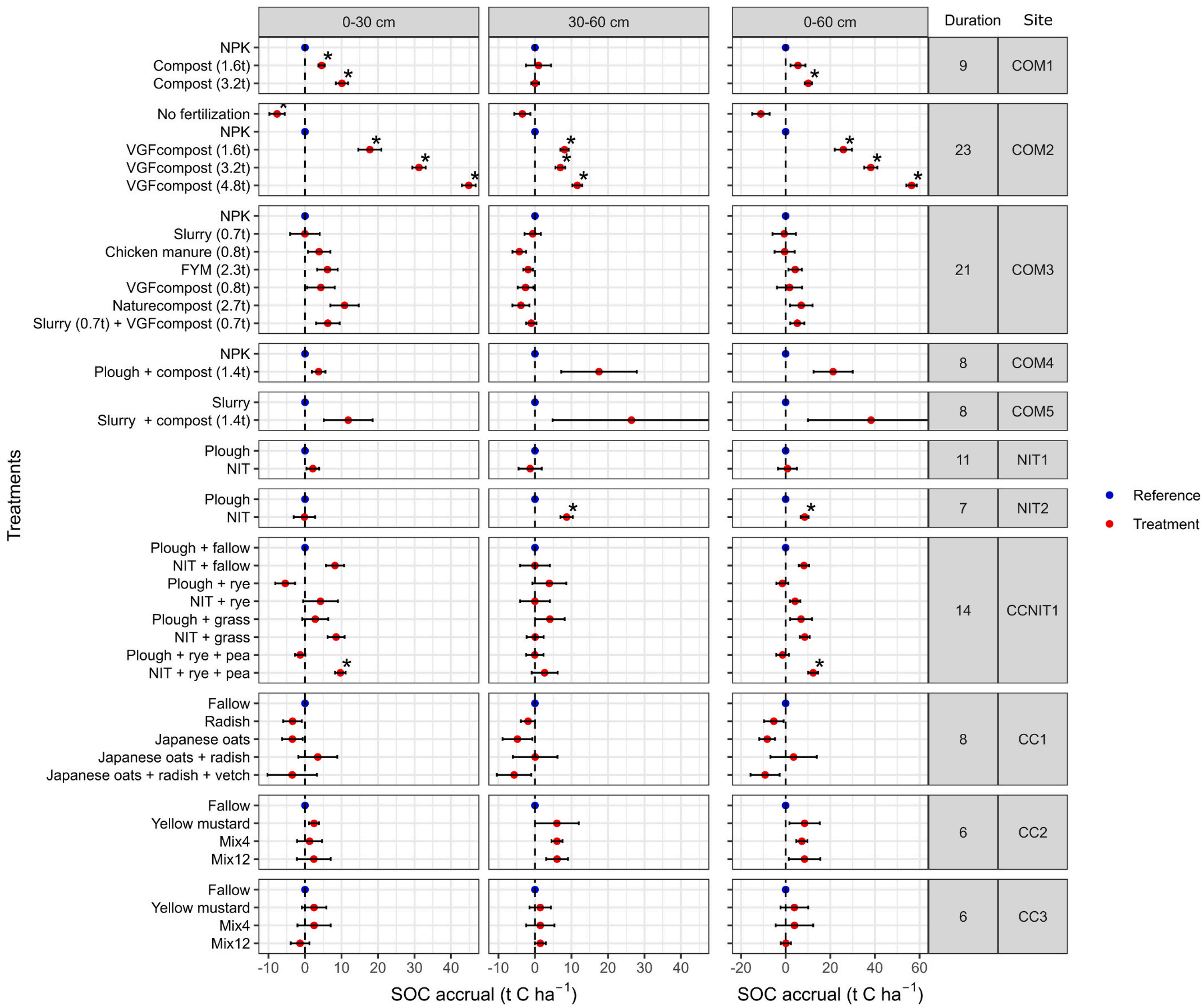

Fig. 4. SOC accrual rate (t C^{-1} ha^{-1} yr^{-1}) for all treatments with an investigated management practice as compared to the reference treatment per management practice in the total depth (0–60 cm). Points indicate the mean per treatment. The asterix (*) indicates significant (p < 0.05) differences between the reference treatment and the treatment with the investigated management practice. Standard management practices were applied in the reference treatments.

climate change mitigation potential (Moinet et al., 2023).

Despite the dependency of SOC accrual on initial SOC levels, this factor is often overlooked in empirical studies and meta-analyses. Many meta-analyses present single-value SOC accrual rates per management practice, without accounting for the variability of these rates across different initial SOC stocks and their non-linear behaviour over time. Multiplying SOC accrual rates from meta-analyses with the surface where the same practice could potentially be implemented to estimate carbon sequestration potentials, as commonly done (Lessmann et al., 2022; Wiesmeier et al., 2020), would therefore lead to inaccurate estimates, at least for our study region.

Furthermore, although a significant knowledge gap remains on the actual SOC stocks after which SOC accrual becomes insignificant, our estimates are within the range found in the literature. We estimated, based on the interaction in our statistical model, that there is a trend towards a null to negative SOC accrual with a reference SOC stocks higher than 54 t C ha^{-1} in the 0–30 cm soil depth layer, at standardized management with 0.8 t organic fertilizer C ha^{-1} yr^{-1} and conventional tillage. This estimate is similar to that of Gocke et al. (2023), who showed that SOC accrual is insignificant with a reference SOC stock of approximately 60 t C ha-1 in the 0–30 cm depth layer. At the long-term trial with more than 100 years of FYM in Rothamsted, 80 t C ha^{-1} in the 0–23 cm depth layer seems to be the threshold above which SOC no longer accrues (Poulton et al., 2018). A recent study showed that SOC stocks average 70 t C ha^{-1} in the 0–30 cm soil depth layer in arable mineral soils in the Netherlands (Knotters et al., 2022). This could mean that the potential for accrual is relatively small compared to our threshold of 54 t C ha^{-1}, and approach the estimate from the long-term Rothamsted experiment.

4.2. Soil depth and the effect of experimental duration

We observed a positive relationship between SOC accrual and experimental duration in the topsoil, similar to other studies (Bai et al., 2019; Gocke et al., 2023; Gross and Glaser, 2021; Poeplau and Don, 2015), but not in the subsoil. The stratified SOC dynamics suggest that organic matter inputs primarily benefit the topsoil, due to limited movement to the subsoil layers, which may be restricted by soil structural attributes or less active biological transport. Most meta-analyses, therefore, consider the topsoil only, although prolonged application of

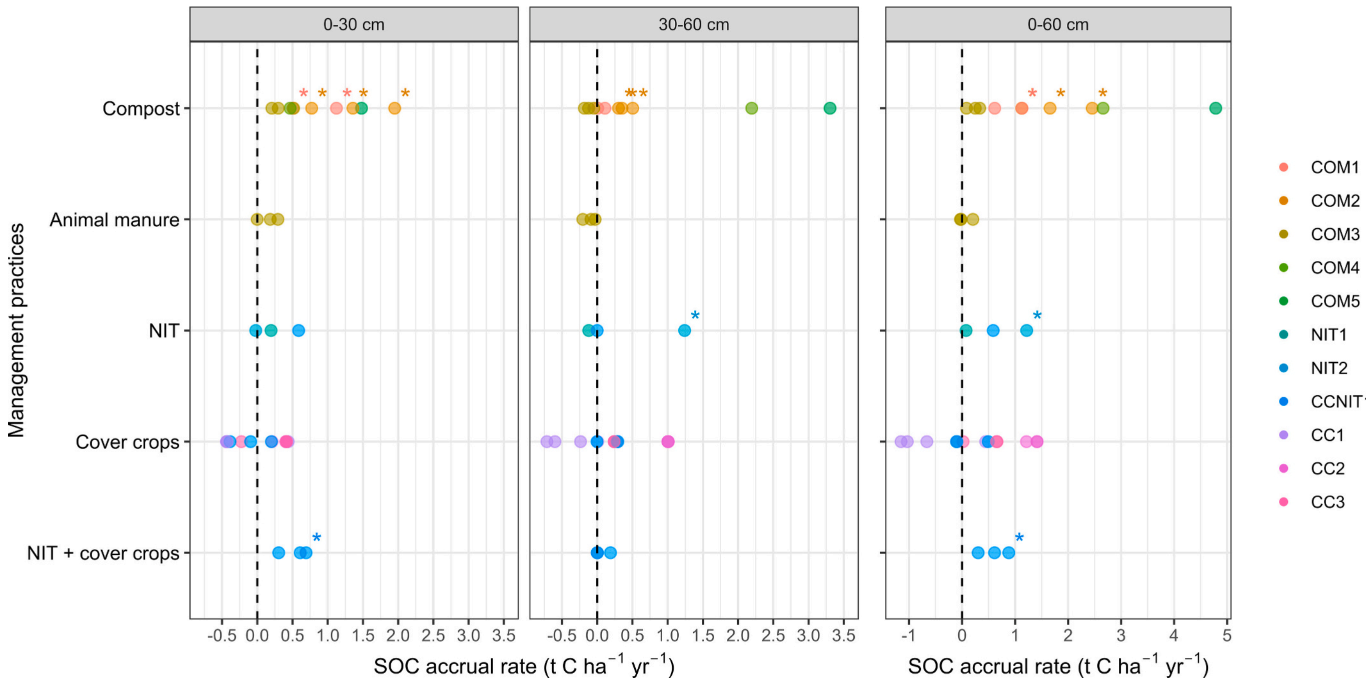

Fig. 5. SOC accrual (t C ha^{-1}) for all treatments with an investigated management practice (red) as compared to the reference (blue) per site in the topsoil (0–30 cm), subsoil (30–60 cm) and total depth (0–60 cm). The asterix (*) indicates significant ($P < 0.05$) differences between the reference treatment and the treatment with the investigated management practice. The amount of organic carbon added through fertilizer is indicated as t C^{-1} ha^{-1} yr^{-1}. Points indicate the mean SOC accrual, and the error bars represent the standard error of the mean (SE). The sites and experimental durations (years) are indicated on the right side of the figure. Standard management practices were applied in the reference treatments.

compost over 23 years did also increase subsoil SOC stocks at COM1. As SOC accrual in the soil takes time, the experimental duration is a crucial factor limiting the detectability of effects of management practices. We had short experimental durations compared to similar studies, such as the one conducted by Gocke et al. (2023) in Germany. This underscores the need for the continuation of field experiments across Northwestern Europe. Furthermore, long time series with uniform measurement methods are crucial to determine whether SOC accrual indeed leads to a net removal of CO_2 from the atmosphere and thus carbon sequestration into the soil (Don et al., 2023). We found that the variability between plots was much higher in sandy soils with high SOC stocks (Fig. S2). This within-site variability has previously been discussed (Poeplau et al., 2016). Effects of agricultural management are minor compared to inherent spatial heterogeneity within a field. Therefore, more replications are needed to determine the impact of management on soil with higher starting SOC stocks. Lastly, we discerned statistical trends of the main drivers of SOC accrual across sites within Northwestern Europe, but a more experimental and controlled approach could benefit the underpinning of the outcomes of this study.

4.3. Improved management practices

Considering the strong effects of initial SOC stocks and experimental duration on SOC accrual and the variability in these properties across our sites, it is unsurprising that, even within our study region, similar improved management practices resulted in different effects across sites. A synthesis of meta-analyses by (Lessmann et al., 2022) reported a SOC accrual rate of 0.42 ± 0.11 t C ha^{-1} yr^{-1} for organic fertilizers in temperate climates in the top 0–20/30 cm. We found varying effects of compost across the sites in Northwestern Europe, with no impact at two sites and higher rates of 1.1 and 2.5 t C ha^{-1} yr^{-1} for the full depth layer ($P < 0.05$) at other sites (COM1 and COM2). None of the animal manure or compost treatments at another site on loam soil (COM3) increased SOC. Meta-analyses specifically considering composts did show consistent effects of compost, but no accrual rates were reported (Crystal-Ornelas et al., 2021). Comparing rates from meta-analyses to our study is challenging because the accrual rates were not related to application rates. Maillard and Angers (2014) calculated that for every ton of manure-C applied to a field, SOC increased by 0.12 t C ha^{-1} yr^{-1}. In our study, at the sites with SOC accrual, this coefficient was higher and ranged between 0.3 and 0.6 t C per t compost-C^{-1} ha^{-1} yr^{-1} in the full soil depth layer. None of the animal manure or compost treatments at another site on loam soil (COM3) increased SOC, even though the field experiment ran for 21 years and had a low reference SOC stock. We think that the lack of complementary synthetic fertilizer reduced effective SOC accrual. This could be attributed to a yield decline (Bakker et al., 2020) and a drop in organic matter addition through crop residues.

Lessmann et al. (2022) reported a SOC accrual rate of 0.10 ± 0.02C ha^{-1} yr^{-1} for intermediate intensity tillage compared to intensive tillage in temperate climates in the top 0–20/30 cm. At one site (NIT2), out of three, we observed significant SOC accrual of 1.2 t C ha^{-1} yr^{-1}, but this was due to an unexpected change in the subsoil. This could be due to the inherent soil heterogeneity at this site. A buildup in the upper layers is generally expected because NIT does not bring any crop residues into the deeper layer, but no increase in the total depth has been found in recent global meta-analyses (Meurer et al., 2018). Despite the site-specific complexities, our overall analyses across all sites and treatments together discerned a trend for SOC accrual in the 0–30 cm layer due to non-inversion tillage but not in the full soil depth layer. The prevalent use of root crops that need intensive soil disturbance for harvesting in Northwestern Europe raises questions about NIT's broader applicability in reducing soil disruption.

A global meta-analysis by Poeplau and Don (2015) reported SOC accrual rates of 0.32 ± 0.08 t ha^{-1} yr^{-1} for the inclusion of cover crops in the crop rotation. Among the four investigated sites, only one treatment at CCNIT1 with a combination of NIT and a cover crop mixture of rye and pea showed SOC accrual with a higher rate of 0.9 t C ha^{-1} yr^{-1} for the full soil depth layer. There was a relatively long experimental duration of 14 years, non-inversion tillage was applied with continuous maize, the reference SOC stock at this site was the lowest among all

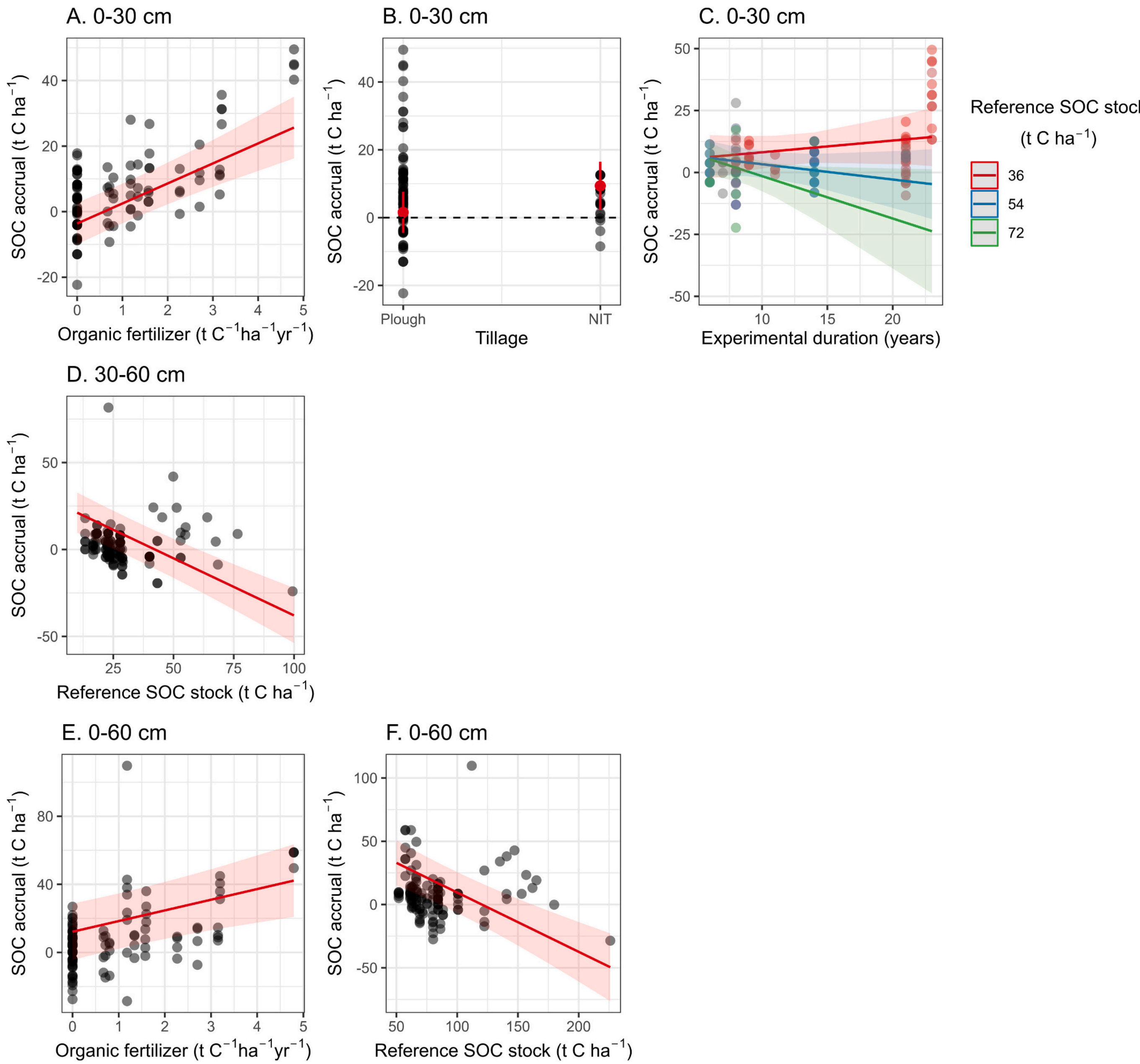

Fig. 6. The marginal effects of significant predictors of SOC accrual (t C ha^{-1}) in the multiple regression model. Panels A–C show marginal effects in the 0–30 cm soil layer: (A) Organic fertilizer input (t C ha^{-1} yr^{-1}), (B) Tillage type (plough vs. non-inversion tillage), (C) Interaction between reference SOC stock and experimental duration (years). Panels D–E show effects in the 30–60 cm soil layer: (D) Reference SOC stock (t C ha^{-1}), (E) Organic fertilizer input. Panel F shows the reference SOC stock (t C ha^{-1}) in the 0–60 cm soil layer. Each panel shows the marginal effects of a given predictor, represented either as a line (continuous predictor) or point (categorical predictor) with 95 % confidence intervals, holding other variables constant. Gray points represent raw data. We used quartiles of the reference SOC stock as moderator values to visualize the interaction in the 0–30 cm layer.

cover crop sites (58 t C ha^{-1}), and cover crop mixtures are known for their ability to generate increased biomass (Barel et al., 2018). Moreover, rye, a frost-resistant species, may have the capacity to regrow after winter, further enhancing its impact on SOC accrual (Seitz et al., 2023). No SOC accrual was observed at the other sites with arable crop rotations (CC1, CC2 and CC3). One reason is that using frost-sensitive cover crop species in arable rotations in Northwestern Europe does not provide enough carbon inputs to show changes against a background of inherent soil heterogeneity. On the other hand, many cover crop experiments face the issue of natural weed development after cash crop harvest that distorts the contrast with the reference treatment (Chaplot and Smith, 2023).

4.4. Conclusion

While international meta-analyses provide valuable insights on average SOC accrual rates at large spatial scales, the reported rates cannot be universally applied across pedoclimatic and agronomic contexts relevant to farmers. Our unified soil sampling across sites enabled a within- and across-site analysis of SOC accrual for different improved management practices. One of our primary findings is that improved management practices can have a varying impact on SOC stocks across various sites within one climatic region. Secondly, we revealed that soils with lower initial SOC are more amenable to SOC accrual through management practices than those with high SOC stocks, which may require more C inputs to increase carbon stocks. Unsurprisingly, compost addition showed the highest effects among the different management practices studied here, likely due to the very high input levels provided. Even this effect was site-dependent, leading to no significant accrual at some sites. The positive impact of compost on SOC accrual for soils with low initial SOC stocks suggests that targeted organic amendments would improve efficiency in SOC sequestration efforts. However, it is worth noting that applying organic fertilizers may lead to a redistribution rather than a net landscape-wide increase in SOC. Our study underscores the importance of considering the local context when adopting management practices. It suggests that initial SOC stocks modulate potentially more than texture the effects of management practices on SOC accrual.

CRediT authorship contribution statement

J.A.B. Schepens: Writing – original draft, Methodology, Conceptualization, Visualization, Formal analysis. **C.J. Koopmans:** Writing – review & editing, Funding acquisition, Project administration, Conceptualization. **D.T. Heupink:** Methodology, Writing – review & editing, Data curation. **B.G.H. Timmermans:** Investigation, Writing – review & editing. **N. Gentsch:** Investigation, Writing – review & editing. **S. Martens:** Investigation, Writing – review & editing. **J. de Haan:** Investigation, Writing – review & editing. **R.E. Creamer:** Writing – review & editing, Conceptualization, Supervision. **G.Y.K. Moinet:** Writing – review & editing, Methodology, Supervision, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT to improve clarity. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Jonas Schepens reports financial support was provided by Ministry of Agriculture. If there are other authors, they 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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geodrs.2025.e00983.

Data availability

Data is stored at Zenedo (https://doi.org/10.5281/zenodo.10813723) and can be requested.

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