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Twenty percent of agricultural management effects on organic carbon stocks occur in subsoils – Results of ten long-term experiments

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ABSTRACT

Agricultural management can influence soil organic carbon (SOC) stocks and thus may contribute to carbon sequestration and climate change mitigation. The soil depth to which agricultural management practices affect SOC is uncertain. Soil depth may have an important bearing on soil carbon dynamics, so it is important to consider depth effects to capture fully changes in SOC stocks. This applies in particular to the evaluation of carbon farming measures, which are becoming increasingly important due to climate change. We sampled and analysed the upper metre of mineral cropland soils from ten long-term experiments (LTEs) in Germany to quantify depth-specific effects on SOC stocks of common agricultural management practices: mineral nitrogen (N) fertilisation, a combination of N, phosphorus (P) and potassium (K) fertilisation, irrigation, a crop rotation with preceding crops (pre-crops), straw incorporation, application of farmyard manure (FYM), liming, and reduced tillage. In addition, the effects of soil compaction on SOC stocks were examined as a negative side effect of agricultural management. Results showed that 19 ± 3 % of total management effects on SOC stocks were found in the upper subsoil (30–50 cm) and 3 ± 4 % in the lower subsoil (50–100 cm), including all agricultural management practices with significant topsoil SOC effects, while 79 ± 7 % of management effects were in the topsoil (0–30 cm). Nitrogen and NPK fertilisation were the treatments that had the greatest effect on subsoil organic carbon (OC) stocks, followed by irrigation, FYM application and straw incorporation. Sampling down to a depth of 50 cm resulted in significantly higher SOC effects than when considering topsoil only. A crop rotation with pre-crops, liming, reduced tillage and soil compaction did not significantly affect SOC stocks at any depth increment. Since approximately 20 % of the impact of agricultural management on SOC stocks occurs in the subsoil, we recommend soil monitoring programs and carbon farming schemes extend their standard soil sampling down to 50 cm depth to capture fully agricultural management effects on SOC.

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Table 1
Overview of sampled long-term experiments (LTEs) with their site properties and environmental conditions. MAT = mean annual temperature; MAP = mean annual precipitation.

Official name of LTE	*LTE name used in this study*	*Coordinates (latitude; longitude)*	*MAT [°C]*	*MAP [mm yr^{-1}]*	*Major soil group (IUSS, 2015)*	*Texture*	*Parent material*	*Start year*	*Associated literature with explanation of experimental design, available research/meta data*
Static Long-term Experiment DDV at Dikopshof	Dikopshof	50.81; 6.95	9.7	634	Luvisol	Silty loam	Loess	1904	Rueda-Ayala et al. (2018); Seidel et al. (2021); Meta data available via the BonaRes Repository (https://lte.bonares.de/lte-details/373/, last accessed: 23 January 2023)
Static Soil Management Experiment BDa_D3 at Berlin-Dahlem	Dahlem	52.47; 3.30	9.6	540	Luvisol	Loamy sand	Periglacial sand	1923	Meta data available via the BonaRes Repository (https://lte.bonares.de/lte-details/372/, last accessed: 23 January 2023) and via GLTEN Metadata Portal (https://glten.org/experiments/229, last accessed: 23 January 2023)
Static Fertilisation and Irrigation Experiment Thy_D1 at Thyrow	Thyrow 1	52.25; 13.23	9.2	510	Cutanic Albic Luvisol	Sand	Periglacial sand	1937	Meta data available via the BonaRes Repository (https://lte.bonares.de/lte-details/379/, last accessed: 23 January 2023) and via GLTEN Metadata Portal (https://glten.org/experiments/246, last accessed: 23 January 2023)
Static Nutrient Deficiency Experiment Thy_D41 at Thyrow	Thyrow 2	52.25; 13.24	9.2	510	Cutanic Albic Luvisol	Sand	Periglacial sand	1937	Ellmer and Baumecker (2005); Meta data available via the BonaRes Repository (https://lte.bonares.de/lte-details/381/, last accessed: 23 January 2023) and via GLTEN Metadata Portal (https://glten.org/experiments/248, last accessed: 23 January 2023)
Nutrient Depletion Experiment NDE at Gießen	Gießen 1	50.60; 8.65	9.0	650	Fluvic Gleyic Cambisol	Silty clay	Floodplain sediments	1954	Macholdt et al. (2019); Research data available via the BonaRes Repository (https://lte.bonares.de/lte-details/375/, last accessed: 23 January 2023)
Fertilisation and Nutrient Gradient Experiment V140 at Müncheberg	Müncheberg	52.52; 14.12	8.4	528	Albic Luvisol (Arenic, Neocambic)	Loamy sand	Aeolian sands over glacial till	1963	Thai et al. (2020); Research data available via the BonaRes Repository (https://doi.org/10.20387/bonares-8fhj-r52g, last accessed: 23 January 2023)
Compaction Experiment Garte-Süd GS (Reinshof) at Göttingen	Göttingen	51.50; 9.94	8.7	645	Luvisol	Clayey loam	Loess	1970	Ehlers et al. (2000); Research data available via the BonaRes Repository (https://lte.bonares.de/lte-details/357/, last accessed: 23 January 2023)
Liming Experiment Dürnast D-II at Freising-Weihenstephan	Dürnast	48.06; 11.07	8.4	820	Cambisol	Sandy loam to loam	Cover sand	1978	Tucher et al. (2018)
Biological Nitrogen Fixation Trial BNF at Gießen	Gießen 2	50.60; 8.65	9.0	650	Fluvic Gleyic Cambisol	Silty clay	Floodplain sediments	1982	Hobley et al. (2018); Meta data available via the BonaRes Repository (https://lte.bonares.de/lte-details/376/, last accessed: 23 January 2023)
International Organic Nitrogen Fertilisation Experiment IOSDV at Rauischholzhausen	Rauischholzhausen	50.76; 8.87	8.1	595	Luvisol	Silty loam	Alluvial sediments	1984	Meta data available via the BonaRes Repository (https://lte.bonares.de/lte-details/378/, last accessed: 23 January 2023) and via GLTEN Metadata Portal (https://glten.org/experiments/277, last accessed: 23 January 2023)

1. Introduction

Agricultural management practices have received considerable attention for their potential to increase SOC stocks and thereby mitigate global climate change (Jobbágy and Jackson, 2000; Powlson et al., 2011b; Stockmann et al., 2013; Minasny et al., 2017). In agriculture, there are additional benefits of increasing SOC stocks, e.g. a greater water-holding capacity and higher water infiltration rate that lead to an enhanced ability in crops to cope with extreme weather events such as droughts or floods (Blanco-Canqui et al., 2013). Improved soil properties also have the potential to increase soil productivity, which can lead to higher yields (Blanco-Canqui et al., 2013). The challenges of a growing world population, resulting in increasing food demand, as well as global warming require more efficient, climate-adapted and sustainable agriculture. Increasing SOC stocks could be one of the key strategies in enabling the agricultural sector to achieve these goals. Developing cropping systems with increased SOC content requires an understanding of the effects of agricultural management on cropland soils. This applies in particular to subsoils, i.e. the soils depths below the tilled soil layers, starting at an average depth of 30 cm. Some reports suggest (e.g., Jobbágy and Jackson, 2000) that more than 50 % of total SOC is stored there, and it is assumed that carbon stocks are more stabilised in deeper soil layers (Gleixner, 2013; Mathieu et al., 2015). For these reasons, subsoils are of special relevance for carbon farming that is expected to achieve negative emissions in agriculture by sequestering carbon into the soil. Hence, it is imperative to assess how management is affecting SOC, yet carbon analyses and scientific studies on SOC are mostly restricted to topsoils (Minasny et al., 2017; Yost and Hartemink, 2020).

The soil sampling depth actually decreased over time, from a peak of 53 cm in the late 1990s to an average of 24 cm between 2004 and 2009, according to the analysis by Yost and Hartemink (2020), who examined articles from four major soil science journals.

To increase OC also in the subsoil, however, it must first reach deeper soil depths. This is possible via leaching of dissolved OC, through bioturbation, or via deep-rooting plants and their exudates (Rumpel and Kögel-Knabner, 2011). Especially OC from roots and root exudates contribute to SOC, more than twice as much as OC from shoots (Kätterer et al., 2011). Consequently, agricultural management practices that stimulate net primary production lead to an increase in SOC stocks in both topsoil and subsoil as a result of increased plant productivity and higher OC input to the soil (Bolinder et al., 2007). Where root-restricting layers occur (e.g. due to high compaction), however, the accessibility of subsoils is hampered (Schneider and Don, 2019). As a result, the build-up of root-derived OC in deeper soil horizons is also impeded.

In arable soils, management practices such as mineral and organic fertilisation, liming, tillage and irrigation can influence SOC stocks. There is little consensus on the overall effect of management practices on subsoil OC owing to the relatively small number of studies that cover subsoil depths (> 30 cm). For instance, while meta-analyses on the effects of mineral fertilisers on SOC stocks included depths down to 60 cm (Alvarez, 2005; Lu et al., 2011), only 2 % of the soil samples were from subsoils, thus demonstrating the underrepresentation of deeper soils. In a meta-analysis of irrigation effects on SOC stocks conducted by Emde et al. (2021), 29 % of the samples were from depths below the topsoil (> 30 cm), while only 5 % contained soil samples from depths greater 60 cm. The effects of organic amendments, such as FYM, have been widely studied for topsoils with consistently positive effects on OC (Maillard and Angers, 2014; Gross and Glaser, 2021; Li et al., 2021). As there are few studies on FYM effects on subsoils and results are inconsistent (Liang et al., 2012; Ghosh et al., 2018; Gross and Glaser, 2021), no reliable conclusions can be drawn. In addition, most studies and meta-analyses that include subsoils do not distinguish between different soil depths within the top metre of soil, impeding conclusions about the depth to which agricultural management affects SOC stocks. Consequently, the extent to which carbon sequestration in cropland below the plough layer can contribute to climate change mitigation is also unknown (Amelung et al., 2020). Several studies show, however, that correct consideration of sampling depth, for instance, is hugely important (Salomé et al., 2010; Rumpel and Kögel-Knabner, 2011; Tautges et al., 2019). The authors highlight that SOC dynamics in the subsoil differ from those in the topsoil, indicating consequences for evaluating the effects of management on SOC. For example, the effects of reduced tillage showed a redistribution of SOC throughout the soil profile, with higher SOC contents in the topsoil but lower SOC contents in the subsoil, offsetting the effects of tillage on SOC across the entire soil profile (Baker et al., 2007). The detection of agricultural management effects in subsoils is often hampered by their greater heterogeneity, as these soil compartments are not homogenised in the way that topsoils are through regular ploughing. In addition, subsoils are affected by the spatial distribution of SOC through substrate inhomogeneities and hotspot OC input, e.g. via root channels (Chabbi et al., 2009).

As changes in SOC stocks tend to be slow and require a period of at least six to ten years before they become apparent (Smith, 2004), long-term experiments (LTEs) are a powerful tool when exploring responses to different agricultural management practices (Dick, 1992; Johnston and Poulton, 2018). Therefore, a comprehensive sampling of ten German LTEs was conducted using a uniform sampling method down to 100 cm depth to close a knowledge gap on the effects of agricultural management on subsoils. This study aims to answer the following questions:

(1) To what soil depth does agricultural management affect SOC stocks?
(2) How strong are management effects on subsoil compared with topsoil?
(3) How does agricultural management influence OC inputs to the soil and thus the build-up of SOC stocks in topsoil and subsoil?

Table 2
Analysed agricultural management practices for each long-term experiment (LTE). For more information on application rates and levels, as well as the number of soil cores and field replicates, see Table A.1 (Appendices A1).

Agricultural management practice	*LTE*
Nitrogen (N) fertilisation	Dikopshof Thyrow 2 Gießen 1 Gießen 2 Rauischholzhausen
Combined nitrogen, potassium and phosphorus (NPK) fertilisation	Dikopshof Thyrow 2 Gießen 1 Gießen 2
Irrigation	Thyrow 1 (Irrigation as experimental factor since 1969)
Liming	Dikopshof Dürnast Dahlem Thyrow 2
Crop rotation with preceding crops (= year-round pre-crops crimson clover and faba bean in rotation with cereals winter wheat, winter rye and spring barley)	Gießen 2
Incorporation of straw	Thyrow 1 (Straw incorporation as experimental factor since 1978) Müncheberg
Farmyard manure	Dikopshof Dahlem (FYM as experimental factor since 1939) Müncheberg Rauischholzhausen
Reduced tillage	Dahlem Göttingen
Soil compaction	Göttingen

2. Materials and Methods

2.1. *The long-term experiments*

Mineral soils from ten German LTEs were sampled from 0-100 cm soil depth to quantify management effects of mineral N and NPK fertilisation, irrigation, a crop rotation with pre-crops, straw incorporation, FYM, liming, reduced tillage and soil compaction on SOC stocks (Table 1).

The analysed soils were identified as Luvisols and Cambisols in accordance with the World Reference Base (WRB) system for soil classification. At the sites, mean annual temperatures range from 8.1 to 9.7 °C and mean annual precipitation from 510 to 820 mm. At the times of sampling (2016, 2017, 2019), LTE durations ranged from 32 to 112 years (median: 58 years, mean: 63 years) (Table 1).

Overall, these LTEs represent Central European arable sites with typical agricultural management, e.g. concerning mineral and organic fertilisation, liming, irrigation and ploughing (Table 2, Table A.1).

2.2. *Soil sampling and sample analysis*

Ten LTEs were sampled between 2016 and 2019. One to three plot-level replicates were taken using a percussion auger with a diameter of 6 cm. This resulted in 8–32 pseudo-replicated samples per site, treatment and depth (mean = 17; reference plots included), depending on the LTE design (Table 1; Table A.1). The cores were then cut into the following four depth increments: 0–30 cm, 30–50 cm, 50–70 cm and 70–100 cm. If horizon boundaries were visible within a sampled depth increment, the core was cut there again and an additional soil sample was collected. All soil material originating from the same depth within one plot was homogenised and weighed to calculate the bulk density of the soil. After samples had been dried at 40 °C, they were sieved at < 2 mm and then weighed to calculate the fine soil mass. They were then stored until further analysis. Total carbon and total N contents were determined via dry combustion using an elemental analyser (EuroEA 3000, HEKAtech, Germany). Total inorganic carbon contents were determined by calcimetry upon reaction with 4 M HCl (ISO 10693, 1995). SOC content was calculated as the difference between total carbon and inorganic carbon content. Soil pH was measured in a suspension of soil and water at a ratio of 1:4. For more information on sample analysis, see Appendices A1.

2.3. Calculation of soil organic carbon stocks and annual organic carbon input

SOC stocks [Mg ha^{-1}] were calculated following Poeplau et al. (2017) using the two equations below:

$$FSS_i = \frac{mass_{fine\ soil}}{surface_{sample}} \tag{1}$$

where FSS_i [Mg ha^{-1}] is the fine soil stock of the investigated soil layer (i), $mass_{fine\ soil}$ is the mass of soil < 2 mm [g] and $surface_{sample}$ is the surface area of the sampling probe [g cm^{-2}], and

$$SOCstock_i = \frac{SOCcon_{fine\ soil}\ x\ FSS_i}{100\ \%} \tag{2}$$

where $SOCcon_{fine\ soil}$ is the SOC content of soil (< 2 mm) [%]. SOC stocks were then corrected for equivalent soil mass to maintain comparability of soil samples as bias in SOC stocks may occur due to differences in bulk density (Wendt and Hauser, 2013) (see Appendices A1). To simplify the evaluation, soil profiles were summarised into three intervals (0–30 cm, 30–50 cm and 50–100 cm) using the weighted arithmetic mean function, with FSS_i as weight. Annual total OC input rates were calculated according to Jacobs et al. (2020) to support the explanation of LTE-specific SOC origin (see Appendices A1). Calculations were based on plot-specific annual yield data from 15 years prior to sampling and crop-specific allocation factors of OC (Bolinder et al., 2007; Jacobs et al., 2020). Exceptions to this were *Göttingen* with annual yield data from five years and *Thyrow 1*, *Thyrow 2* and *Dahlem* with annual yield data from 20 years prior to sampling.

Harvest residues were removed from the field at *Dikopshof*, *Dahlem*, *Thyrow 1* (except straw-fertilised plots), *Thyrow 2*, *Gießen 1*, *Müncheberg* (except straw-fertilised plots), *Gießen 2* and *Rauischholzhausen* (except straw-fertilised plots).

2.4. Other Calculations

Total management effects ($\Delta SOC\ stock_{total}$; [Mg ha^{-1}]) of the complete soil profile (0–100 cm) were calculated according to Eqs. 3–6:

$$\Delta SOC\ stock_{total} = \sum_{i=1}^{3} x_i \tag{3}$$

where x is the difference in SOC stocks of the agricultural management practice (= treatment) and the reference of the respective depth interval i (0–30 cm, 30–50 cm and 50–100 cm);

$$x_1 = SOC\ stock_{Treatment_{0-30cm}} - SOC\ stock_{Reference_{0-30cm}};\ [\mathrm{Mg}\ ha^{-1}] \tag{4}$$

$$x_2 = SOC\ stock_{Treatment_{30-50cm}} - SOC\ stock_{Reference_{30-50cm}};\ [\mathrm{Mg}\ ha^{-1}] \tag{5}$$

$$x_3 = SOC\ stock_{Treatment_{50-100cm}} - SOC\ stock_{Reference_{50-100cm}};\ [\mathrm{Mg\ ha}^{-1}] \tag{6}$$

Relative proportions of management effect to total effects per depth interval, P_i [%], were calculated according to Eq. 7:

$$P_i = \frac{x_i}{\Delta SOC\ stock_{total}} \times 100 \tag{7}$$

Relative SOC stock changes due to agricultural management practices compared with the SOC stock of the respective reference per depth interval, C_i [%], were calculated according to Eq. 8:

$$C_i = \frac{x_i}{SOC\ stock_{Control_i}} \times 100 \tag{8}$$

To determine the subsoil strength of the tested agricultural management practice and to enable a comparison between the management practices, a topsoil/subsoil value *TS* was calculated (Eq. 9). The smaller the number, the stronger the subsoil effect:

$$TS = \frac{x_1}{x_2 + x_3} \tag{9}$$

Site-specific differences in annual total OC input rates [$\Delta OC\ input$; Mg ha^{-1} yr^{-1}] and cumulative OC inputs [$OC\ input_{cum}$; Mg ha^{-1}] were calculated according to Eqs. 10 and 11:

$$\Delta OC\ input = OC\ input_{Treatment} - OC\ input_{Reference} \tag{10}$$

$$OC\ input_{cum} = \Delta OC\ input \times t \tag{11}$$

where t is the sum of the years in which the respective treatment was carried out.

The complete dataset resulting from the soil sampling campaigns and the data produced by further calculations are available in Appendices A2.

2.5. Statistical analysis

Soil samples from the lower subsoil (50–100 cm) of the NPK fertilised plots in *Gießen 2*, the straw amended plots in *Müncheberg* and the plots in *Rauischholzhausen* where FYM was applied had to be excluded as there was considerable subsoil heterogeneity that could not be captured with the field replicates and therefore biased the results. Linear mixed-effects analyses of the relationship between agricultural management practice (= treatment) and SOC stocks were performed using the *lme4* package (Bates et al., 2015). To test a particular treatment (binary variable), plots were selected that were fertilised with NPK and differed only in the treatment being tested. N-fertilised and NPK-fertilised plots were compared with plots without N or NPK. Treatment and depth level were entered as fixed effects with an interaction term. Different depth levels within a soil core were considered as paired samples. To ensure independent observations, a random intercept and slope model based on the smallest AIC value was chosen with random intercepts for sites and random slopes for depth levels. If normal quantile-quantile and residual plots of the R package *DHARMa* (Hartig, 2021, version 0.4.3) revealed any deviations from normality or homoscedasticity, a square root transformation was applied prior to model fitting. For each treatment, estimated marginal means of SOC stocks and contrasts between treatment and reference plots per depth level (0–30 cm, 30–50 cm and 50–100 cm) were produced using the *emmeans* package (Lenth, 2021, version 1.6.3). The same approach was tested for aggregated depth levels from 0-50 cm and 0–100 cm to identify effects of the respective treatment on cumulative SOC stocks. To detect differences within SOC stock differences at the 0–30 cm and 0–50 cm depth intervals, a one-sample t-test was performed. Mean values are presented along with their standard error. Significance was set at a level of $\alpha = 0.05$. In cases where the differences between control and treatment were not significant, we explicitly stated this and avoided the term "effect". Instead, we described the general direction of depth profiles. All statistical analyses were conducted using R (version 4.0.3).

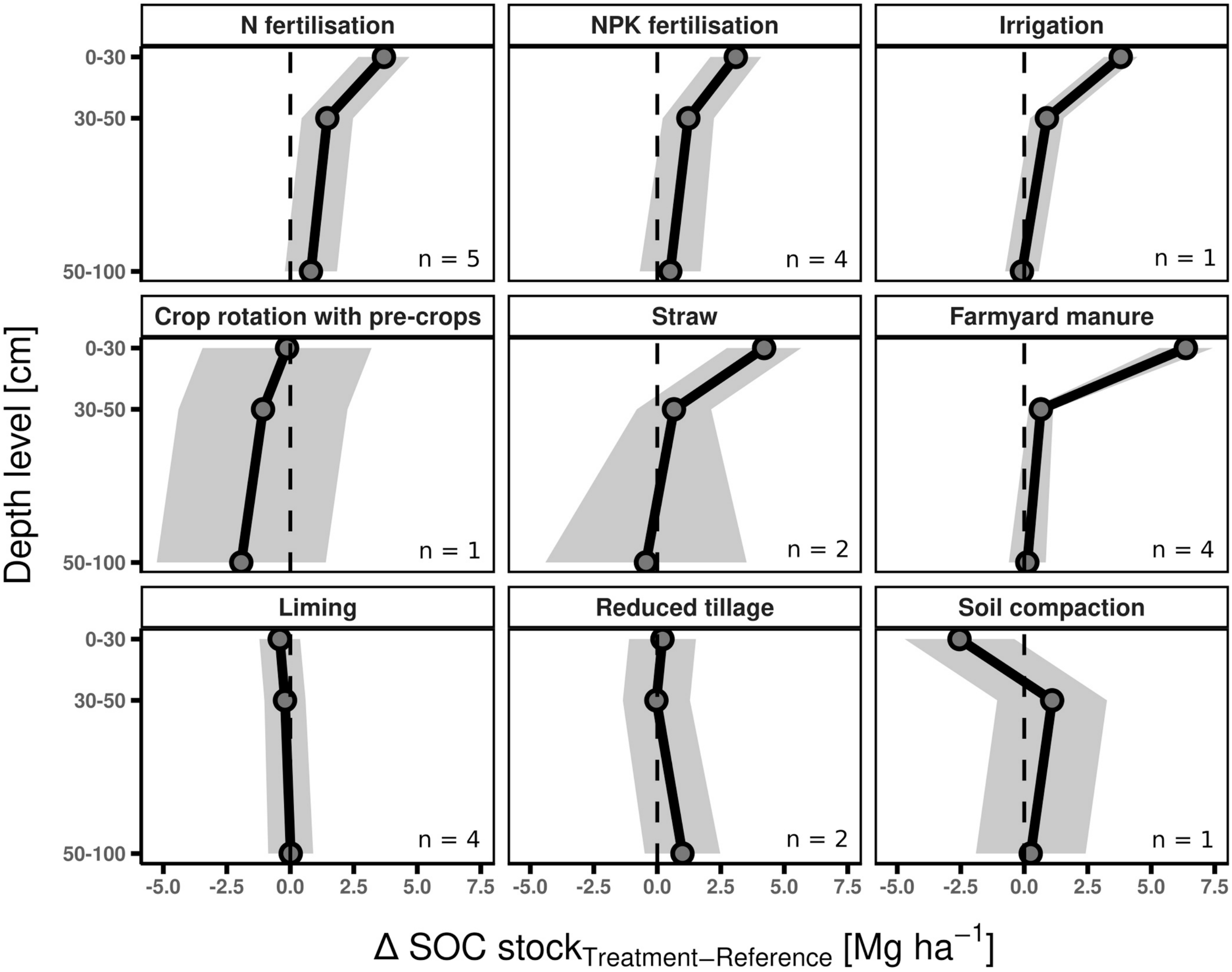

Fig. 1. Effects of agricultural management on soil organic carbon (SOC) stocks at different depth intervals down to 100 cm (n = number of sites). Average SOC stock differences per depth interval are shown as dots. Grey areas represent the standard error of the mean. The dashed line at x = 0 means that SOC stock$_{\text{Reference}}$ = SOC stock$_{\text{Treatment}}$. N = nitrogen, P = phosphorus, K = potassium.

3. Results

3.1. Changes to organic carbon stocks in topsoil and subsoil

The treatments that had significant topsoil effects on SOC stock were mineral N and NPK fertilisation, irrigation, straw incorporation and FYM application. Their relative proportion of total management effects (P_i) were on average 78.6 ± 6.7 % in the topsoil (0–30 cm), 18.7 ± 3.0 % in the upper subsoil (30–50 cm), and 2.8 ± 4.1 % in the lower subsoil (50–100 cm).

Mineral N and NPK fertilisation, irrigation, straw incorporation and FYM application resulted in significantly higher SOC stocks down to 50 cm. Mineral fertilisation with N and NPK had the greatest effect on subsoil SOC stocks, as indicated by the lowest TS value of 1.7. This was followed by irrigation (4.7), FYM (8.2) and straw incorporation (19.6) (Appendices A2). Differences in SOC stocks decreased with depth. For SOC stocks deeper than 50 cm, none of the treatments had a significant impact. Crop rotation with pre-crops, liming, reduced tillage and soil compaction did not significantly affect SOC stocks across all depth increments (Fig. 1).

Mineral fertilisation enhanced SOC stocks in the topsoil at all sites by 3.7 ± 1.0 Mg ha^{-1} (N) and 3.1 ± 1.0 Mg ha^{-1} (NPK) on average, as well as in the upper subsoil (N: 1.5 ± 1.0 Mg ha^{-1}; NPK: 1.2 ± 1.0 Mg ha^{-1}) and lower subsoil (N: 0.8 ± 1.0 Mg ha^{-1}, NPK: 0.5 ± 1.2 Mg ha^{-1}) (Fig. 1). Site-specific analysis revealed a negative SOC stock difference of -0.2 ± 0.1 Mg ha^{-1} for *Gießen 1* at 30–50 cm depth and -0.3 ± 0.1 Mg ha^{-1} for *Dikopshof* at 50–100 cm depth (Fig. 2). As shown in Fig. 3, each 10 kg of additional N increased OC stocks by on average 6 kg in the topsoil (R^2 = 0.84) and 2 kg in the subsoil down to 50 cm (R^2 = 0.40).

Irrigation resulted in higher SOC stocks in the topsoil (3.8 ± 0.7 Mg ha^{-1}) and upper subsoil (0.9 ± 0.7 Mg ha^{-1}), but the SOC stock difference was almost zero (-0.1 ± 0.7 Mg ha^{-1}) in the lower subsoil (Fig. 1). Irrigation enhanced SOC stocks in the upper subsoil by 30 % compared to non-irrigated plots of the same depth interval (Fig. 4).

The year-round pre-crops in rotation with cereals led to lower SOC stocks throughout the soil profile, with non-significant SOC stock differences of -0.1 ± 3.3 Mg ha^{-1} in the topsoil, -1.1 ± 3.3 Mg ha^{-1} in the upper subsoil and -1.9 ± 3.3 Mg ha^{-1} in the lower subsoil (Fig. 1).

Straw incorporation increased SOC stocks at 0–30 cm depth by 4.2 ± 1.5 Mg ha^{-1} and at 30–50 cm depth by 0.7 ± 1.5 Mg ha^{-1} (Fig. 1), except for *Thyrow 1* at 50–100 cm depth with a negative SOC stock of -0.4 ± 0.2 Mg ha^{-1} due to the treatment (Fig. 2). Straw incorporation enhanced SOC stocks in the upper subsoil by 16 % compared to the reference plots of the same depth interval (Fig. 4).

Among all the significant treatments, FYM enhanced SOC stocks in topsoil the most by 6.4 ± 1.1 Mg ha^{-1} (Fig. 1). Positive SOC stock

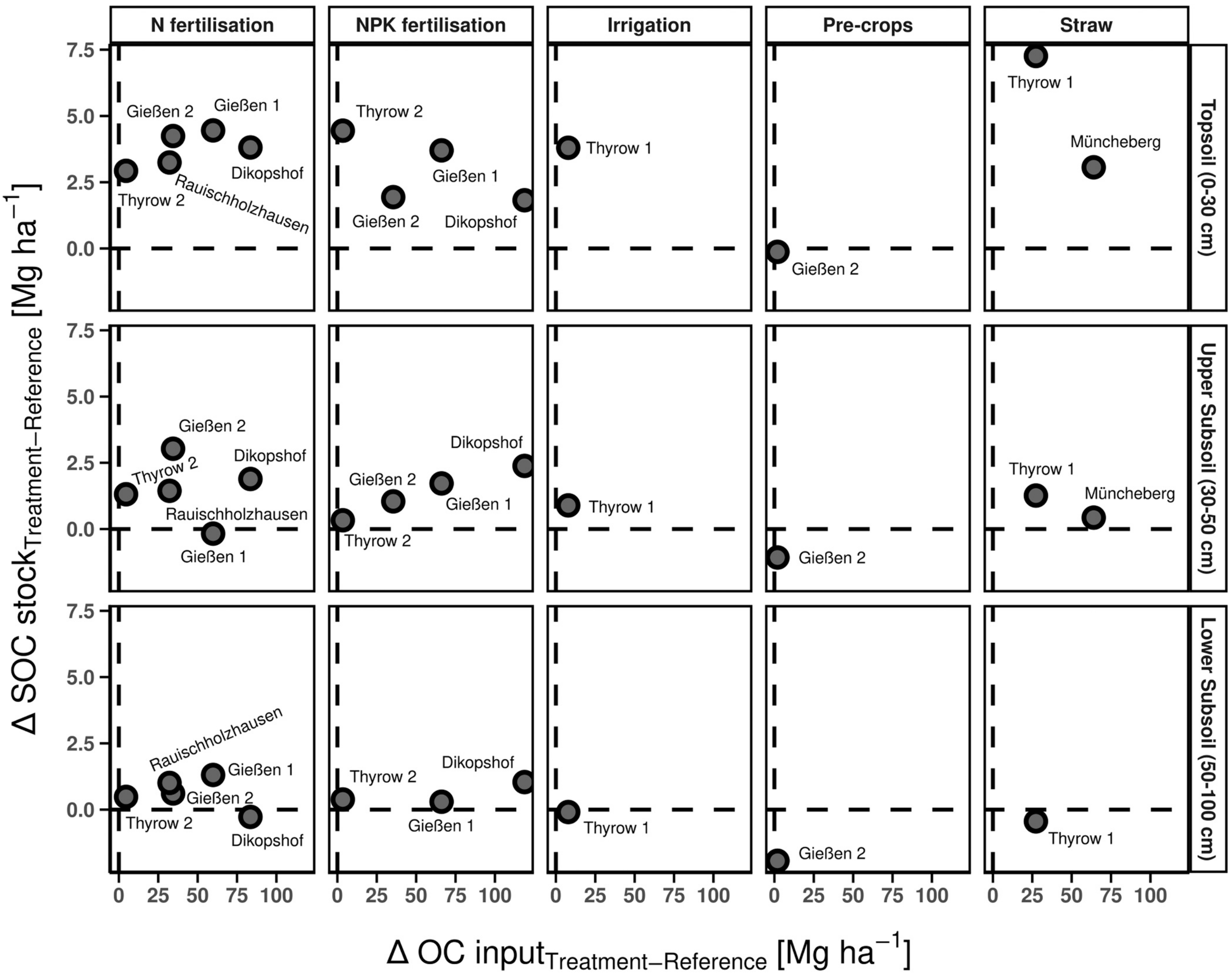

Fig. 2. Site-specific and depth-specific soil organic carbon (SOC) stock differences compared to the additional organic carbon (OC) input as a result of the agricultural management mineral fertilisation with nitrogen (N), phosphorus (P) and potassium (K), irrigation, crop rotation with preceding crops ("Pre-crops"), and incorporation of straw. The x-axis shows the differences between the OC input due to the agricultural management practice and the corresponding reference (no differentiation according to depth intervals). The OC input was multiplied by the respective duration of the long-term experiment. The y-axis shows the differences between the SOC stock due to the agricultural management practice and the corresponding reference. The dashed line at x = 0 means that OC input$_{\text{Reference}}$ = OC input$_{\text{Treatment}}$. The dashed line at y = 0 means that SOC stock$_{\text{Reference}}$ = SOC stock$_{\text{Treatment}}$.

differences also occurred in the upper subsoil (0.7 ± 0.5 Mg ha^{-1}) and lower subsoil (0.1 ± 0.7 Mg ha^{-1}). Considering site-specific effects, *Rauischholzhausen* revealed a negative SOC stock difference of -0.5 ± 0.3 Mg ha^{-1} in the upper subsoil (Fig. 5).

Liming had no significant effects on SOC stocks in 0–100 cm. Soil organic carbon stocks in the topsoil and upper subsoil were reduced by 0.4 ± 0.8 Mg ha^{-1} and 0.2 ± 0.8 Mg ha^{-1} (Fig. 1), respectively. No SOC stock differences could be detected in the lower subsoil (0.0 ± 0.9 Mg ha^{-1}). Only in *Dikopshof* did liming cause higher SOC stocks of 3.2 ± 1.6 Mg ha^{-1} in the topsoil (Fig. 5). Liming increased soil pH by an average of 0.9 in the topsoil, 1.1 in the upper subsoil and 0.4 in the lower subsoil, resulting in soil pH values of 6.9 for both the topsoil and upper subsoil, and 6.6 for the lower subsoil (Appendices A2).

Reduced tillage depths led to non-significant differences in SOC stocks throughout the soil profile. The topsoil and lower subsoil SOC stocks were higher (0.2 ± 1.3 Mg ha^{-1}; 1.0 ± 1.5 Mg ha^{-1}), but the difference in the upper subsoil was close to zero (0.0 ± 1.3 Mg ha^{-1}) (Fig. 1). Site-specific comparisons between *Dahlem* and *Göttingen*, however, showed a contrasting pattern above 50 cm in terms of SOC stock changes: SOC stock changes for *Dahlem*, the sandy site, were positive in the topsoil (4.2 ± 2.1 Mg ha^{-1}) and negative in the upper subsoil (-0.5 ± 0.2 Mg ha^{-1}), whereas the differences for *Göttingen*, the loamy site, were negative in the topsoil (-5.3 ± 2.6 Mg ha^{-1}) and positive in the upper subsoil (0.6 ± 0.3 Mg ha^{-1}). For both sites, a reduced tillage depth resulted in higher SOC stocks in the lower subsoil (*Dahlem*: 0.8 ± 0.4 Mg ha^{-1}; *Göttingen*: 1.3 ± 0.6 Mg ha^{-1}) (Fig. 5).

Soil compaction did not reveal any evidence of significantly affecting SOC stocks at 0–100 cm. Topsoil SOC stocks were reduced by 2.5 ± 2.2 Mg ha^{-1}, but enhanced in the upper subsoil (1.1 ± 2.2 Mg ha^{-1}) and lower subsoil (0.3 ± 2.2 Mg ha^{-1}) (Fig. 1).

3.2. Changes in organic carbon input to the soil

Mineral fertilisation enhanced belowground and aboveground primary production (Appendices A2) and thus crop residues, which in turn led to significantly higher OC inputs to the soil. Fertilisation with NPK resulted in +0.8 ± 0.3 Mg C ha^{-1} yr^{-1} (≙ 56 Mg C ha^{-1} with an average LTE duration of 67 years), and N fertilisation led to +0.8 ± 0.2 Mg C ha^{-1} yr^{-1} (≙ 43 Mg C ha^{-1} with an average LTE duration of 61 years). Irrigation had no significant effect on OC input (+0.2 ± 0.1 Mg C ha^{-1} yr^{-1}

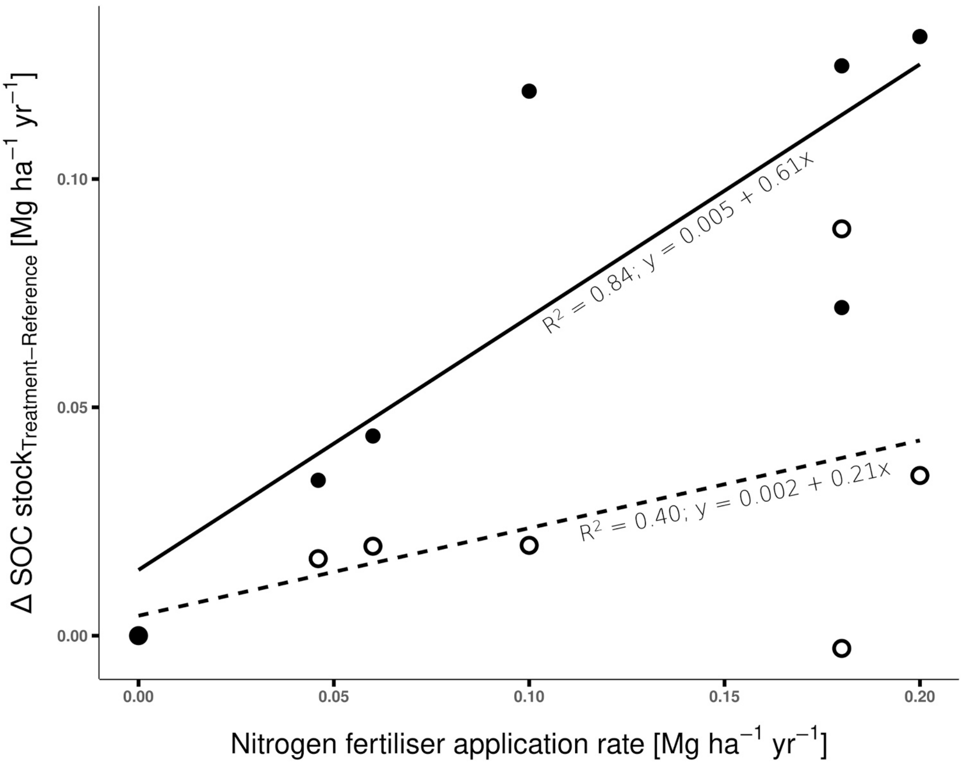

Fig. 3. Soil organic carbon (SOC) stock differences in topsoil (0–30 cm; black circles, solid regression line) and subsoil (30–50 cm; white circles, dashed regression line) divided by the respective duration of the long-term experiment [Mg ha^{-1} yr^{-1}] due to applied nitrogen (N) fertiliser rates [Mg ha^{-1} yr^{-1}] at the five LTEs that contributed to the N fertilisation treatment.

or 8 Mg C ha^{-1} with an average duration of 47 years) compared with the respective reference (Fig. 2). Straw incorporation increased annual OC input significantly by +1.0 ± 0.2 Mg C ha^{-1} yr^{-1} (≙ 46 Mg C ha^{-1} with an average LTE duration of 46 years). A crop rotation with pre-crops had no significant effect on OC input (+0.1 ± < 0.1 Mg C ha^{-1} yr^{-1}; 2 Mg C ha^{-1} with an average LTE duration of 34 years) (Fig. 2). On average, the greatest changes in OC input rates were the result of FYM application (+1.7 ± 0.6 Mg C ha^{-1} yr^{-1} or 132 Mg C ha^{-1} with an average LTE duration of 69 years), which caused a significant increase at each LTE. The changes were highest at sites with the highest FYM application rates of 12 (*Dikopshof*) and 30 Mg C ha^{-1} yr^{-1} (*Dahlem*) and the longest durations of FYM application (112 and 77 years). Liming had no significant effect on OC input (+0.1 ± 0.1 Mg C ha^{-1} yr^{-1} or 6 Mg C ha^{-1} with an average LTE duration of 81 years). Differences in OC inputs rates were on average -0.3 ± 0.3 Mg C ha^{-1} yr^{-1} (≙ -16 Mg C ha^{-1} with an average LTE duration of 71 years) due to reduced tillage, with significantly lower OC input rates at Göttingen but non-significant changes at Dahlem (Appendices A2). Soil compaction had no significant effects on OC input (-0.2 ± 0.1 Mg C ha^{-1} yr^{-1} or -5 Mg C ha^{-1} with an LTE duration of 24 years).

4. Discussion

4.1. *Mineral fertilisation with N and NPK*

Mineral N and NPK fertilisation led to higher SOC stocks throughout the soil profile, including the subsoil (Fig. 1). On average, topsoil SOC stocks increased by 9 % and subsoil SOC stocks by 6 % (Fig. 4). This can be attributed to an increased net primary production (Appendices A2) and subsequent increased input of roots and crop residues into the soil (Glendining et al., 2009; Kirchmann et al., 2013; Bolinder et al., 2020). The importance of crop residues left in the field for SOC accumulation has been highlighted by Alvarez et al. (2005) who found even negative effects on SOC stocks after crop residue removal despite mineral fertilisation. The present study examined plots that had been cleared of aboveground crop residues, but stubbles remained in the field. Nearly 75 % of the total OC input was caused by belowground crop residues, i.e. roots and rhizodeposition (Appendices A2). This may explain why the subsoil OC response of mineral fertilisation was the strongest among all the treatments, as indicated by the lowest TS value of 1.7. This is related to the effectiveness of root OC inputs to increase SOC stocks being more than double that of shoot-derived OC inputs (Kätterer et al., 2011). A meta-analysis by Lopez et al. (2022) concluded that root length and root biomass decreased by 9 % and 7 %, respectively, due to N limitation, while root length per shoot biomass and root-to-shoot ratio increased by 33 % and 44 %, respectively, indicating that crops under limited nutrient conditions invest more in belowground growth to maintain nutrient acquisition. In order to develop these positive effects in subsoil, roots and root exudates must reach the subsoil, which requires it to be uncompacted. Crops bred for deeper and bushier root systems (Kell, 2011) and soils free of root-restricting soil layers (Schneider and Don, 2019) can promote OC inputs to reach the subsoil.

Nitrogen fertilisation could also have a positive effect on aggregate stability by increasing the input of fresh crop residues (Six et al., 1999). This may result in lower susceptibility of particulate OC to decomposition, which can also lead to higher SOC stocks after N fertilisation (Chang et al., 2019; Lu et al., 2021; Meng et al., 2022).

SOC stocks rose with increasing mineral N fertilisation (Fig. 3). While Kätterer et al. (2012) report a 1/1 OC sequestration rate, meaning that every mass unit of N applied results in the same amount of OC increase in the topsoil, the present results suggested a lower sequestration rate of 1/0.6 in the topsoil and of 1/0.2 in the subsoil. The average duration of the experiments at the sites included was close to 60 years in both studies. Since the present study, however, included an experiment with a duration of 112 years (*Dikopshof*), the observed differences in OC accumulation rates could be explained by a new equilibrium being reached at *Dikopshof* between OC gain and OC loss.

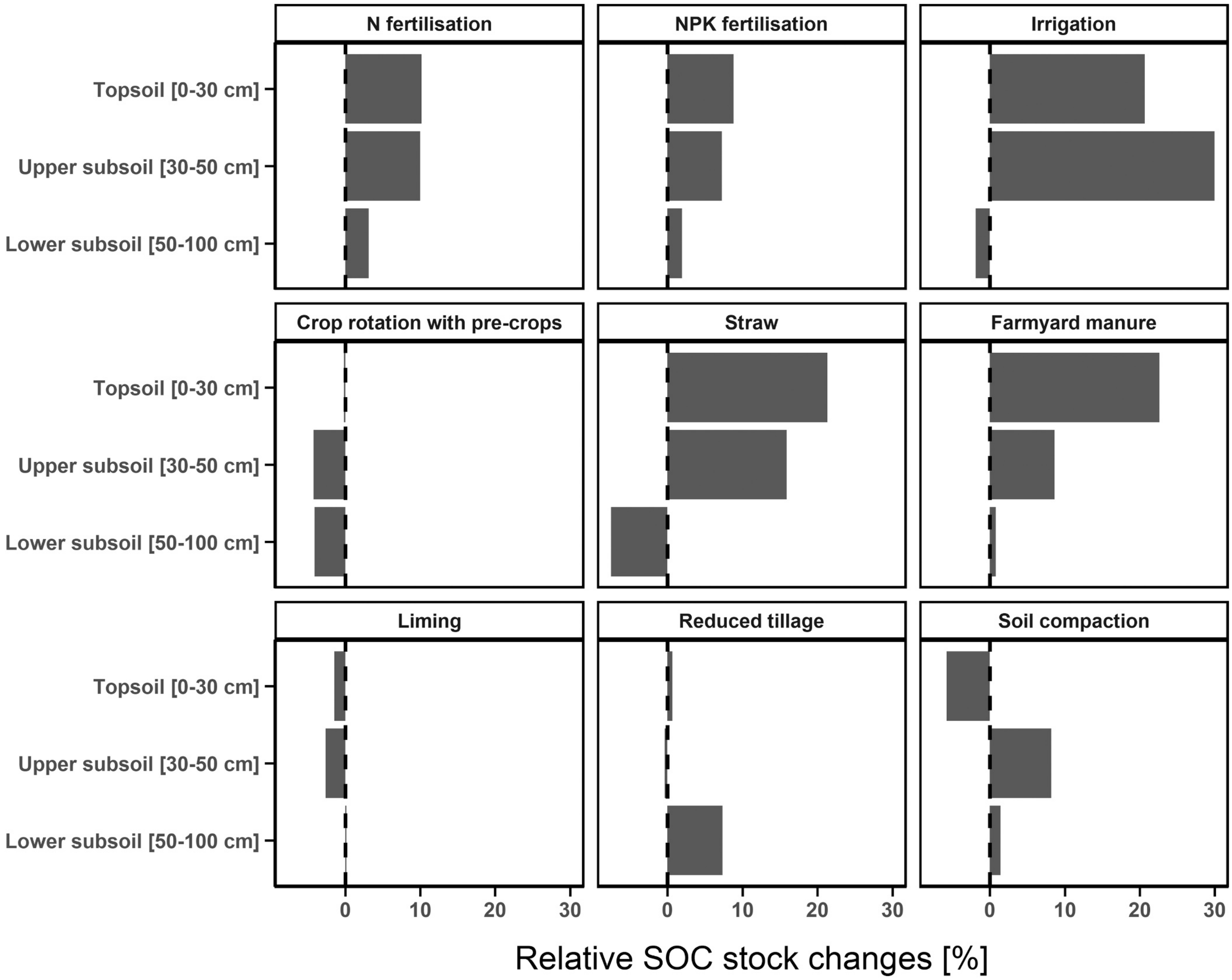

Fig. 4. Relative soil organic carbon (SOC) stock changes (C_i) due to agricultural management practices compared with the SOC stock of the corresponding reference per depth interval.

4.2. *Irrigation*

A meta-analysis by Emde et al. (2021) on irrigation effects at 42 study sites that included subsoil found an average increase in SOC stocks of 6 % for soils depths down to 100 cm, but without detecting significant effects deeper than 10 cm. In contrast, the present study found effects down to 50 cm depth, with an average increase of 5 Mg SOC ha^{-1} at 0–100 cm depth, of which 17 % occurred in the subsoil. The Thyrow site has the lowest mean average precipitation (510 mm) of all investigated sites and a mean average temperature of 9.2 °C. At *Thyrow 1*, irrigation was therefore an effective treatment since net primary production was increased by 24 % (Appendices A2). As a result, OC input were higher (+8 Mg ha^{-1}) and thus SOC stocks increased. This is consistent with the results of Wu et al. (2008), who also found higher SOC stocks, particularly between 10 and 60 cm, after 50 years of irrigation. The authors attribute the effect to the crop root-derived OC input as the root density was very high within this section.

Considering the small number of replicates, but the simultaneous confirmation of the results by other studies, we conclude that irrigation is a promising method to ensure or stimulate root growth and agricultural productivity, thereby increasing SOC stocks in both topsoil and subsoil.

4.3. *Crop rotation with pre-crops*

Year-round pre-crops crimson clover (*Trifolium incarnatum*) and faba bean (*Vicia faba*) in rotation with the cereals winter wheat (*Triticum aestivum* ssp. *aestivum*), winter rye (*Secale cereale*), and summer barley (*Hordeum vulgare*) had no significant effect on SOC stock in comparison to maize (*Zea mays*) in rotation with the same three cereals. Crimson clover and faba bean are legumes that are able to fix atmospheric N and incorporate it in their plant tissues to meet their own N demands. It is also available to subsequent crops after mineralisation from legume crop residues. Legumes therefore have the potential to reduce the need for N fertiliser (Peoples and Craswell, 1992; Hobley et al., 2018). They can also develop a deep root system (> 1.5 m) that can increase SOC in the subsoil (Gaiser et al., 2012; Kautz et al., 2013). Nevertheless, the present study did not provide significant evidence that legume cultivation affects SOC stocks at depths of 0–100 cm for the specific crop rotation in these plots. Crop rotations can vary widely, and since only one site with a particular crop rotation was studied, these results must be confirmed elsewhere for validation or falsification. Therefore, no general conclusions can be drawn from these data.

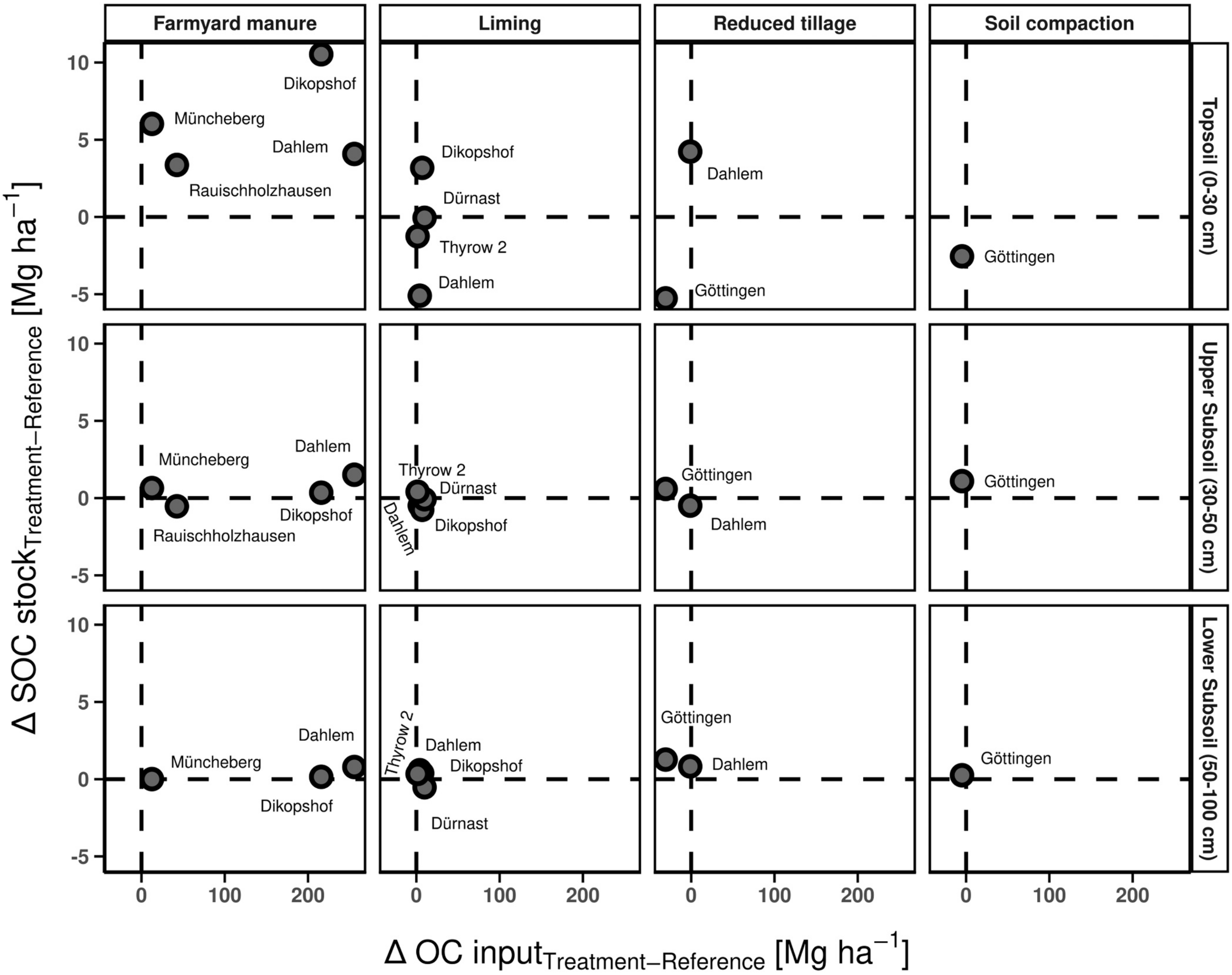

Fig. 5. Site-specific and depth-specific soil organic carbon (SOC) stock differences compared to the additional organic carbon (OC) input as a result of the agricultural management practices farmyard manure, liming, reduced tillage, and soil compaction. The x-axis shows the differences between the OC input due to the agricultural management practice and the corresponding reference (no differentiation according to depth intervals). The OC input was multiplied by the respective duration of the long-term experiment. The y-axis shows the differences between the SOC stock due to the agricultural management practice and the corresponding reference. The dashed line at $x = 0$ means that OC $\text{input}_{\text{Reference}} = \text{OC input}_{\text{Treatment}}$. The dashed line at $y = 0$ means that SOC $\text{stock}_{\text{Reference}} = \text{SOC stock}_{\text{Treatment}}$.

4.4. Straw

Effects of straw incorporation on SOC vary widely, with some authors reporting higher SOC stocks (e.g. Saffih-Hdadi and Mary, 2008; Liu et al., 2014; Cong et al., 2020; Getahun et al., 2022), and others finding non-significant or negative effects (Plénet et al., 1993; Campbell et al., 2001; Curtin and Fraser, 2003; Lemke et al., 2010; Powlson et al., 2011a). Here, positive effects of straw incorporation on SOC stocks were found to a depth of 50 cm, with an average increase in SOC stocks of 19 %. Similarly, straw enhanced OC inputs by 74 % at *Müncheberg* and by 105 % at *Thyrow 1* (Appendices A2). The effect of incorporated crop residues on SOC stocks decreased with depth and is related to the fact that straw was incorporated only into the topsoil. Indeed, Getahun et al. (2022) found that incorporation of straw beneath the plough horizon at 29–34 cm depth resulted in an average SOC increase of 157 %, at least in the short term (1–3 years), supporting the hypothesis that incorporation depth limits the effect of straw on subsoil depth.

Straw is poor in N, but microbes depend on sufficient N availability to build up stabilised SOC in the long term, which is why N deficiency results in lower conversion rates (Mary et al., 1996). Agricultural systems, however, receive N with mineral or organic fertilisers, which allows for the build-up of long-term stabilised SOC with straw. There is ongoing debate as to whether straw can be removed and used as bioenergy or for other purposes without compromising SOC and soil functions (Lal, 2005; Weiser et al., 2014; Poeplau et al., 2015). The present findings indicate that straw incorporation is important for building up SOC in both the topsoil and the subsoil, although only two sites were investigated.

4.5. Organic fertilisation with farmyard manure

Farmyard manure application increased topsoil SOC stocks the most of all the treatments analysed. Subsoil studies about FYM manure effects on SOC stocks are rare. Bhattacharyya et al. (2011) studied soil samples from a 32-year-old LTE in India and found significantly higher SOC stocks down to 45 cm depth, with an increase of 11 Mg ha^{-1} in the topsoil and 8 Mg ha^{-1} in the subsoil, equivalent to a TS value of 1.4. Gami et al. (2009) analysed three Nepalese LTEs with a duration of 23–25 years and observed significantly higher SOC stocks of 2.2 Mg ha^{-1} down to 15 cm and insignificant effects with +0.4 Mg ha^{-1} at subsoil depths (> 30 cm), corresponding to a TS value of 6.3. The present results are in between these two studies, with a total SOC stock increase of 7 Mg ha^{-1} down to

100 cm. Farmyard manure effects on SOC stocks mainly occurred in the topsoil (89 %) with TS values of 8 (0–100 cm) and 10 (0–50 cm). In contrast, mineral fertiliser reaches deeper soil layers more easily (TS = 1.7, see Results) through vertical leaching and thus stimulates plant productivity also in the subsoil (Bolinder et al., 2007). As a result, more root-derived litter and root exudates can also contribute to higher subsoil OC stocks. Farmyard manure, in contrast, remains mainly in the topsoil, where it is applied and incorporated (Liang et al., 2012). The incorporation of FYM, however, reduces the bulk density of the soil (Celik et al., 2004) and stimulates deep-burrowing earthworm activity (Andersen, 1983), which facilitates the vertical movement of (dissolved) FYM-OC into deeper soil layers through leaching and bioturbation and can therefore also increase SOC stocks in the subsoil (Rumpel and Kögel-Knabner, 2011), albeit to a lesser extent.

4.6. Liming

Liming is a common management practice to maintain crop productivity by balancing the pH to a near neutral value (Haynes and Naidu, 1998; Holland et al., 2018; Junior et al., 2020). It further improves soil structure through its ability to increase aggregate stability, thus influencing SOC dynamics (Rowley et al., 2018).

The present results showed that liming had no significant effects on SOC stocks at 0–100 cm. Liming increased pH values at the four investigated sites by an average of 0.8 pH units in the topsoil and 1.0 pH units in the subsoil. Considering these sites individually, the effects of liming were inconsistent at different depths, with either positive or negative differences in SOC stock (Fig. 5). Contrasting effects of liming on SOC stocks can be explained by a stimulation of microbial activity under less acidic conditions, leading to increased SOC mineralisation and thus SOC losses (Wong et al., 2010; Paradelo et al., 2015), but also increased OC input due to improved plant-growing conditions, which can cause an increase in SOC stocks (Bronick and Lal, 2005; Briedis et al., 2012). In the present study, OC inputs were on average 0.1 Mg ha^{-1} yr^{-1} higher in limed soils than in non-limed soils, which is equivalent to a relative increase of 7 %.

Previous liming studies have revealed comparable non-significant and inconsistent effects on SOC. Wang et al. (2016) analysed topsoil and subsoil ($\leq$ 50 cm) effects of liming on SOC in two LTEs with a duration of 22 and 30 years, but found significant effects only at 0–10 cm, where SOC content decreased due to liming. At a depth of more than 10 cm, SOC content was also depleted or remained unchanged, although not significantly so. Paradelo et al. (2015) found that 50 % of the studies evaluated in a meta-analysis on cropland showed positive effects of liming on SOC stock, 17 % showed negative effects and 33 % showed non-significant effects. None of the cropland studies analysed soils deeper than 20 cm, highlighting that subsoil is underrepresented in SOC studies.

4.7. Tillage

The present results showed that reduced tillage had no significant effects on SOC stocks at 0–100 cm. The two tillage experiments in the present study (*Göttingen* and *Dahlem*), however, emphasised that SOC changes in the topsoil can point in a different direction to SOC changes in the subsoil. Sampling topsoil only is not sufficient to assess the effects of different tillage practices (i.e. depth, frequency, turning or loosening) on SOC (Baker et al., 2007). Many studies in temperate climates involving subsoil have only found a redistribution of SOC in the soil profile between 0 and 100 cm, but no total significant increase in SOC (Luo et al., 2010; Haddaway et al., 2017; Meurer et al., 2018). This is similar to a study by Krauss et al. (2022) on nine European reduced tillage trials under organic farming: SOC stocks were higher in the topsoil and lower in the upper subsoil under reduced tillage. They also found that subsoil heterogeneity in field experiments could bias management effects on SOC. A comprehensive meta-analysis by Haddaway et al. (2017) found no significant differences in the subsoil between tillage treatments. Yet, only 19 % of the studies (66 of 351) included soil depths exceeding 30 cm.

It is noteworthy that the two sites studied here had opposite SOC patterns above 50 cm, with smaller SOC stock differences in the topsoil at *Göttingen* and greater differences in the upper subsoil, while SOC stock differences were higher in the topsoil at *Dahlem* and lower in the upper subsoil. Thus, it can be concluded that factors other than reduced tillage must have influenced the increase or decrease in SOC stocks, such as different experimental durations and tillage treatments, and possibly climatic factors.

4.8. Soil compaction

The use of heavy machinery in agriculture exerts high pressure on arable soils and can lead to soil compaction (Lipiec et al., 2003). Schneider and Don (2019) recently estimated that about 10 % of Germany's cropland is anthropogenically compacted beyond critical limits. Yet, the effect of soil compaction on SOC stocks has received limited scrutiny to date. This study analysed one LTE (*Göttingen*) in which traffic-induced soil compaction was carried out once in 1995. The results showed that 24 years after compaction, the SOC stock in 0–100 cm was not significantly different from that of the non-compacted reference. The topsoil revealed a SOC stock decrease by 2.6 Mg ha^{-1} after compaction. The upper subsoil showed the opposite result, with a 1.1 Mg ha^{-1} higher SOC stock in the compacted soil samples. Deurer et al. (2012) found the same pattern in an apple orchard in New Zealand where the carbon content was significantly higher under a compacted wheel track than in the non-compacted reference soil, suggesting that this compaction reduced the water infiltration rate and thus the loss of carbon in dissolved form. Moreover, microbial activity might be reduced after compaction due to oxygen limitation (Torbert and Wood, 1992). Therefore, higher SOC stocks in the compacted samples from 30 to 50 cm are probably due to prevented OC loss rather than OC gain. Annual OC input rates were negative in the compacted plots, confirming the negative effects of compaction on productivity and thus on the long-term build-up potential of SOC stocks. These results, however, contradict those of Ehlers et al. (2000), who found a reversion of compaction at *Göttingen* by bioturbation, root growth and tillage within a few years of mechanical compaction. In 1997, reduced yield differences due to compaction could no longer be observed.

5. Conclusions

This study highlights the importance of subsoils, since significant impacts of agricultural management on SOC stocks were found down to 50 cm depth. Topsoil (0–30 cm) accounted for 78.6 ± 6.7 % of the total management effects, upper subsoil (30–50 cm) for 19 ± 3 % and lower subsoil (50–100 cm) for 3 ± 4 %. Mineral fertilisation, irrigation and organic amendments had the largest effects on SOC stocks down to 50 cm. Considering that approximately 20 % of total management effects occur in subsoils, an incomplete picture emerges if the build-up or loss of SOC is only assessed for topsoils. In particular, the results presented here have consequences for soil monitoring programs whose goal is to quantify changes in SOC stocks. So far, SOC changes in mineral soils under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2022 tend to be reported for topsoils only (IPCC, 2006). To avoid under- or over-estimation of agricultural management impacts on SOC stocks, however, it is recommended that SOC stock changes down to 50 cm depth are reported, thus including the upper subsoil as well.

CRediT authorship contribution statement

SLB, MIG, WA, EUH, FS and AD performed soil sampling across the different LTEs. JG, US, KS, BH, SS and MS also supported sampling at

Table A.1
Analysed agricultural management practices for each long-term experiment (LTE) with application rates or levels of reference and treatment plots. N = nitrogen; P = phosphorus; K = potassium.

Agricultural management practice	*LTE*	*Reference*	*Treatment*	*Number of soil cores per plot (for pooled samples, see 2.2)*	*Number of field replicates (control plots)*	*Number of field replicates (treatment plots)*	*Sum of soil cores (treatment and control plots)*
N fertilisation	Dikopshof	N: 0 kg ha^{-1} yr^{-1}	N: 46 kg ha^{-1} yr^{-1}	2	2	2	8
	Thyrow 2		N: 60 kg ha^{-1} yr^{-1}	3	4	4	24
	Gießen 1		N: 180 kg ha^{-1} yr^{-1}	2	4	4	16
	Gießen 2		N: 180 kg ha^{-1} yr^{-1}	1	4	4	8
	Rauischholzhausen		N: 100, 200 kg ha^{-1} yr^{-1}	1	6	3	9
NPK fertilisation	Dikopshof	N: 0 kg ha^{-1} yr^{-1} P_2O_5: 0 kg ha^{-1} yr^{-1} K_2O: 0 kg ha^{-1} yr^{-1}	N: 46, 70, 94 kg ha^{-1} yr^{-1} P_2O_5: 70, 100, 130 kg ha^{-1} yr^{-1} K_2O: 140, 200, 260 kg ha^{-1} yr^{-1}	2	2	2	8
	Thyrow 2		N: 60, 90 Mg ha^{-1} yr^{-1} P_2O_5: 55 kg ha^{-1} yr^{-1} K_2O: 125 kg ha^{-1} yr^{-1}	3	4	4	24
	Gießen 1		N: 180 kg ha^{-1} yr^{-1} P_2O_5: 45, 90 kg ha^{-1} yr^{-1} K_2O: 60, 120 kg ha^{-1} yr^{-1}	2	4	4	16
	Gießen 2		N: 180 kg ha^{-1} yr^{-1} P_2O_5: 45 kg ha^{-1} yr^{-1} K_2O: 60 kg ha^{-1} yr^{-1}	1	4	4	8
Irrigation	Thyrow 1 (Irrigation as experimental factor since 1969)	0 mm yr^{-1}	20–484 mm yr^{-1} (1971–2016), median 104 mm yr^{-1}	3	3	3	18
Liming	Dikopshof	CaO: 0 kg ha^{-1} yr^{-1}	CaO: 800 kg ha^{-1} yr^{-1}	2	4	4	16
	Dürnast		liming to pH 6.0–6.4, liming to pH 6.8–7.0	1	8	4	12
	Dahlem		CaO: 263 kg ha^{-1} yr^{-1}	2	3	3	12
	Thyrow 2		CaO: 157 kg ha^{-1} yr^{-1}	3	4	4	24
Crop rotation with pre-crops (= year-round pre-crops crimson clover and faba bean in rotation with cereals winter wheat, winter rye and spring barley)	Gießen 2	Maize (*Zea mays*), followed by three subsequent crops: winter wheat (*Triticum aestivum* ssp. *aestivum*), winter rye (*Secale cereale*), and summer barley (*Hordeum vulgare*)	Pre-crops: Crimson clover (*Trifolium incarnatum*) and faba bean (*Vicia faba*), followed by three subsequent crops: winter wheat (*Triticum aestivum* ssp. *aestivum*), winter rye (*Secale cereale*), and summer barley (*Hordeum vulgare*)	2	8	8	32
Incorporation of straw	Thyrow 1 (Straw incorporation as experimental factor since 1978)	0 Mg ha^{-1} yr^{-1}	4 Mg ha^{-1} yr^{-1} dry matter	3	3	3	18
	Müncheberg		2 Mg ha^{-1} yr^{-1} dry matter	1	8	8	16
Farmyard manure	Dikopshof	0 Mg ha^{-1} yr^{-1}	120 Mg ha^{-1} yr^{-1}	2	6	6	24
	Dahlem (FYM as experimental factor since 1939)		30 Mg ha^{-1} yr^{-1}	2	6	6	24
	Müncheberg		10 Mg ha^{-1} yr^{-1}	1	16	16	32
	Rauischholzhausen		3.2 Mg ha^{-1} yr^{-1}	1	6	6	12
Reduced tillage	Dahlem	30 cm	17 cm	2	6	6	24
	Göttingen	28 cm	10 cm	1	4	4	8
Soil compaction	Göttingen	No mechanical loading/ unwheeled	Single mechanical loading with 6 × 5 Mg (number of wheel passes times wheel load)	1	4	4	8

given LTEs. FS, MIG, JG, KK and SLB provided data on soil parameters and DB, BH, YV, US, KS, SJS, SS and MS provided yield data of the studied LTEs and considerable additional information to understand the experiments. The NIR spectra from which the predicted soil texture data emerged were prepared by JG and EUH. Data preparation prior to analysis was performed by FS and LES. The formal analyses were carried out by LES. LES, FS and AD visualised the data. LES and AD wrote the article in collaboration with all the authors.

Declaration of Competing Interest

The authors declare that they have no conflict of interests.

Data Availability

Data are included in the supplement.

Acknowledgements

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Appendices A1

See Table A.1.

Additional information on sample analysis (see Section 2.2 in the main document)

Electrical conductivity was measured in a suspension of soil and water at a ratio of 1:4. Sand, silt and clay contents were derived via visible near infrared light reflectance spectroscopy (VNIR) by applying models that were trained on a representative subset of soil samples from all LTEs (Hobley and Prater, 2019).

Mass correction of soil organic carbon (SOC) stocks

SOC stocks were corrected for equivalent soil mass ($SOCstock_{corr}$ of the investigated soil layer (i) [Mg ha^{-1}]) to maintain comparability of soil samples, as bias in SOC stocks may occur due to differences in bulk density (Wendt and Hauser, 2013). We used the LTE-specific median ($median_{fine\ soil}$ [g]) of the fine soil mass and the SOC content ($SOCcon_{fine\ soil}$ [g]) of the soil layer to be mass corrected (Equation A.1).

$$SOCstock_{corr_i} = SOCcon_{fine\ soil}\ x\ \frac{median_{fine\ soil}}{surface_{sample}} \tag{A.1}$$

If additional soil core cuts were made within the original intervals i (0–30 cm; 30–50 cm; 50–70 cm; 70–100 cm), the upper part of the respective depth interval a (0-x cm; 30-x cm; 50-x cm; 70-x cm) was not mass corrected and added to the lower part of the depth interval b (x-30 cm; x-50 cm, x-70 cm; x-100 cm) which was mass corrected with a correction term *corr* (Equation A.2 and A.3).

$$SOCstock_{corr_i} = SOCcon_{fine\ soil_a} \times \frac{mass_{fine\ soil_a}}{surface_{sample}} + SOCcon_{fine\ soil_b} \times \frac{mass_{fine\ soil_b} - corr}{surface_{sample}} \tag{A.2}$$

$$corr = mass_{fine\ soil_i} - median_{fine\ soil_i} \tag{A.3}$$

Calculation of annual organic carbon (OC) input

Annual total OC input rates were calculated in order to support explanation of LTE-specific SOC origin. Annual aboveground (C_input_{above} [Mg ha^{-1}]), belowground (C_input_{below} [Mg ha^{-1}]) and total OC inputs (C_input_{total} [Mg ha^{-1}]) of crops and organic fertiliser ($C\_input_{organic}$ [Mg ha^{-1}]) on arable sites were calculated in order to explain differences in SOC stocks (Equation A.4-A.7). As described and calculated by Jacobs et al. (2020), we used crop-specific OC allocation coefficients (CA_x) and determined the total annual net primary production (NPP_{total} [Mg ha^{-1}]) with the help of annual yield data of 15 years before sampling. Exceptions are *Göttingen* with annual yield data of five years and *Thyrow 1*, *Thyrow 2* and *Dahlem* with annual yield data of 20 years, respectively. Afterwards, following equations delivered above mentioned OC input rates:

$$C\_input_{above} = NPP_{total} \times CA_{HR} + NPP_{total} \times CA_{ST} \tag{A.4}$$

(HR = harvest residues; ST = stubbles).

Harvest residues were removed from the field at *Dikopshof*, *Dahlem*, *Thyrow 1* (except straw-fertilised plots), *Thyrow 2*, *Gießen 1*, *Müncheberg* (except straw-fertilised plots), *Gießen 2* and *Rauischholzhausen* (except straw-fertilised plots) ($CA_{HR} = 0$).

$$C\_input_{below} = NPP_{total} \times CA_{R} + NPP_{total} \times CA_{RD} \tag{A.5}$$

(R = roots; RD = rhizodeposition)

$$C\_input_{organic} = FER_{org} \times DM_{FER} + C_{FER} \tag{A.6}$$

(FER_{org} = fresh matter amount of applicated organic fertiliser [Mg ha^{-1}]; DM_{FER} = dry matter content of organic fertiliser [Mg ha^{-1}]; C_{FER} = organic carbon content of organic fertiliser [Mg ha^{-1}])

$$C\_input_{total} = C\_input_{above} + C\_input_{below} + C\_input_{organic} \tag{A.7}$$

Appendix B. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108619.

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