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Interactive effects of agricultural management on soil organic carbon accrual: A synthesis of long-term field experiments in Germany

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ABSTRACT

Crop production often leads to soil organic carbon (SOC) losses. However, under good management practice it is possible to maintain and even re-accumulate SOC. We evaluated how different cropland management techniques affected SOC stocks in the topsoil (0–30 cm depth) of 10 long-term experiments (LTE) in Germany. We found that SOC stocks were particularly enhanced by mineral fertilization and organic amendments like straw incorporation and to a smaller degree by irrigation, but only slightly affected by the choice of preceding crops. In agreement with global *meta*-analyses, liming and reduced tillage had little or even negative effects on SOC storage, but effects also depended on fertilization. Management effects on SOC stocks were dependent on soil texture: sandy soils showed the lowest SOC stocks of 20.9 ± 2.3 (standard error of the mean) Mg ha^{-1}, but exhibited the largest relative response to different management options. Annual changes in SOC stocks ranged from −3.0 ‰ with no mineral N fertilization, to + 6.1 ‰ with farmyard manure application, using the mineral-fertilized and limed treatment as reference. Even higher rates of up to + 10.6 ‰ yr^{-1} were reached with the combination of irrigation and straw incorporation. Note that the contribution of organic amendments to SOC accrual and thus to climate change mitigation must be adjusted for reduction in SOC at sites from which straw was removed. Overall, the potential of agricultural management to influence and enhance SOC stocks is significant. This potential is controlled by soil type and land-use duration, is largest for sandy soils with overall lowest SOC stocks, and is characterized by antagonistic and synergistic effects of different management practices.

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1. Introduction

Soil organic matter, with soil organic carbon (SOC) as the largest component, is important for soil health and fertility and thus for optimum crop growth conditions and food security (Andrews et al., 2004; Oldfield et al., 2019; Wander et al., 2019). In addition, carbon sequestration in arable soils may contribute to climate change mitigation (Amelung et al., 2020; Lal et al., 2018; Lessmann et al., 2022; Zomer et al., 2017). National and international efforts such as the '4 per mille' initiative (https://www.4p1000.org) encourage stakeholders and farmers to implement strategies that promote SOC accrual, thereby supporting sustainable agricultural management, food security and climate change mitigation (Le Foll et al., 2018; Minasny et al., 2017). Nevertheless, direct comparisons of long-term SOC accumulation rates for different treatments in a given region or country are scarce.

Decades of agricultural soil management and climate change have resulted in SOC losses (Sanderman et al., 2017), and in many agroecosystems decreases in SOC are ongoing, both on regional (e.g., Steinmann et al., 2016) and global scales (Lal, 2004; Smith et al., 2016). Thus, arable soils often store significantly less SOC than they are potentially able to (Chen et al., 2018; Paustian et al., 2016; Wiesmeier et al., 2013), which has led to the assumption that improved management could turn arable soils into enormous natural carbon sinks (FAO, 2019). Several studies have estimated C sequestration potentials between 0.2 and 1.15 Mg ha^{-1} yr^{-1} (Lessmann et al., 2022; McBratney et al., 2014; Powlson et al., 2014; Zomer et al., 2017). It is widely accepted that significant SOC accumulation is achieved when reconverting arable land into forest (Aubrey et al., 2019) or grassland (Lugato et al., 2015; Poeplau et al., 2011). Less is known about the effects of the various agricultural management techniques on SOC gain or loss (McBratney et al., 2014), particularly when several agricultural measures are combined.

The main goal of agricultural soil management is to meet the nutrient and water demand of crops and thus to ensure sufficient crop yields (FAO, 2017). A well-balanced soil nutrient status can be achieved by mineral (nitrogen [N] + phosphorus [P] + potassium [K]) fertilization, and in certain cases by liming to avoid soil acidification and to improve both nutrient availability (Holland et al., 2018; Kirkham et al., 2007) and soil structure (Filipek, 2011). Another effective tool to support fertility of soils may be the application of organic amendments, which can, in case of farmyard manure or slurry, supply considerable amounts of nutrients and improve other soil functions (e.g., Singh et al., 2020), which can potentially elevate SOC stocks at a given site. However, this may occur at the expense of SOC accrual at sites from which the organic matter was removed, thus limiting the respective climate mitigation potential (Amelung et al., 2020; Lessmann et al., 2022).

Apart from fertilization, there are also technical and biological means to enhance SOC stocks. In Germany, the average plowing depth in conventional agriculture is 31 ± 0.1 cm (Schneider and Don, 2019), but reduced tillage, for example, by reducing tillage depth or frequency, or adoption of no-till farming is also increasingly applied in order to preserve soil structure and thus reduce the erosion susceptibility of soils, despite risks such as yield declines due to increased weed and disease pressure (Cooper et al., 2016; Peigné et al., 2007). Another important technical means is irrigation, which is often needed in regions that are frequently affected by water-deficit during the growing season, such as in Northeast Germany. However, the effects of irrigation on SOC accrual are ambiguous, as it increases primary production and thus biomass input to soil (Trost et al., 2013; Zhou et al., 2016), but also adds to SOC mineralization (Chenu et al., 2019). Preceding crops (that is, crops cultivated prior to the main cropping season; hereafter referred to as precrops) may change soil physical and chemical properties; particularly leguminous crops are known for their positive effects of reducing greenhouse gas emission, and are thought to promote SOC accumulation in the long-term (Jensen et al., 2012). Also, improved growth of subsequent crops may contribute to SOC stock gain, as compiled by Stagnari et al. (2017).

From a global perspective, Lessmann et al. (2022) identified that organic amendments, either alone or combined with mineral fertilization, were the management strategy with the highest impact on SOC stocks in arable land, which strongly exceeds the increase of SOC stocks caused by improved tillage techniques or crop management. However, after integrating different climatic zones, the authors stated that impacts of different management strategies might be highly overestimated on the global scale due to upscaling issues. This highlights the need for quantification of the effects of management strategies on SOC stock changes on the regional or national level.

To the best of our knowledge, the long-term effects of agricultural management techniques, and combinations thereof, on SOC gain or loss have not been analyzed systematically for arable soil in Germany, which leaves the following questions open: Which agricultural management measures protect existing SOC stocks or even increase them in the long-term? How much SOC gain do these measures generate? Which measures are detrimental for SOC storage and how much SOC loss do they cause? At what rate do changes in SOC stocks occur?

A comprehensive data set on the current status of SOC stocks of agricultural soils in Germany was published recently (Poeplau et al., 2020a, b). As this data set combines hundreds of sites across Germany, each with a different management history, a systematic and quantitative evaluation of the long-term effects of agricultural management on existing SOC stocks and their changes over time remains challenging. Therefore, in the present study, we aimed to disentangle the long-term effects of several management techniques on SOC stocks of German arable land, with the most important and common techniques being mineral fertilization, organic amendments and liming, as well as their combinations. To this end, we sampled 10 long-term experiments (LTE) in Germany with more than 30 years of static management, comprising prevalent management techniques (mineral fertilization, organic amendments, liming) as well as further soil and crop management measures (pre-crop cultivation, irrigation and tillage), and combinations of these measures. This allowed the first direct comparison and ranking of individual and combined agricultural techniques, and thus also potential synergistic or antagonistic effects on SOC accrual within one country, as well as an evaluation of how texture and land-use duration affect SOC stock changes across the different agricultural management use options.

2. Material and methods

2.1. LTE sites and selected treatments

We investigated 10 German agricultural LTEs with minimum durations of 30 years. The LTEs (see Fig. 1 for locations) were established between 1904 and 1984 on soils comprising mostly Luvisols developed on various parent materials including periglacial sand, loess and floodplain sediments (Table 1). All of the study sites had a humid, temperate climate (Köppen-Geiger climate classification Cfb). Mean annual precipitation was lowest in East German LTEs (BDa_D3, Thy_D1, Thy_D41, V140) and highest in the South German LTE (D-II). Overall, our study included major types of conventional agricultural soil management, as well as gradients in soil texture and climatic regimes (Table 1).

In all LTEs except D-II and GS, mineral fertilization was included as a factor in our sampling, that is, there were either treatments without mineral fertilization and fully mineral-fertilized treatments (Thy_D41, DDV, BSG, EV), and/or application or omission for one or more of the main nutrient elements nitrogen (N; V140, Thy_D1, Thy_D41, IOSDV, DDV, BSG and EV, given at 2 rates at IOSDV), phosphorus (P; Thy_D41, BDa_D3, DDV and EV) and potassium (K; DDV and EV). At V140, N was given at five different rates from which four levels (N1, N2, N4, N5) were included in the current study.

Treatments with organic amendments included farmyard manure (FYM) application in BDa_D3, V140, DDV and IOSDV, and straw incorporation at Thy_D1 (here combined with green manure), V140 and IOSDV (here combined with additional mineral N fertilization, rapeseed as a catch crop [crop grown between two main crops, e.g., in winter to catch excessive N] and digestate from a biogas plant). Straw application was performed via plowing and incorporation of straw biomass of the grown cereal crop. At V140, organic amendments comprised three levels (FYM1, FYM2, straw), from which the treatment with the higher FYM rate and the straw treatment were included in the current study.

Liming was included as a factor in BDa_D3, Thy_D41, D-II and DDV, and was applied either in fixed amounts (BDa_D3, DDV) or in varying amounts to reach/maintain a certain pH value (Thy_D41, D-II).

Tillage intensity was investigated at BDa_D3, where soil is either plowed with a moldboard plow to a depth of 28 cm or to a shallower depth of 17 cm, and at GS, where soil was either regularly plowed or

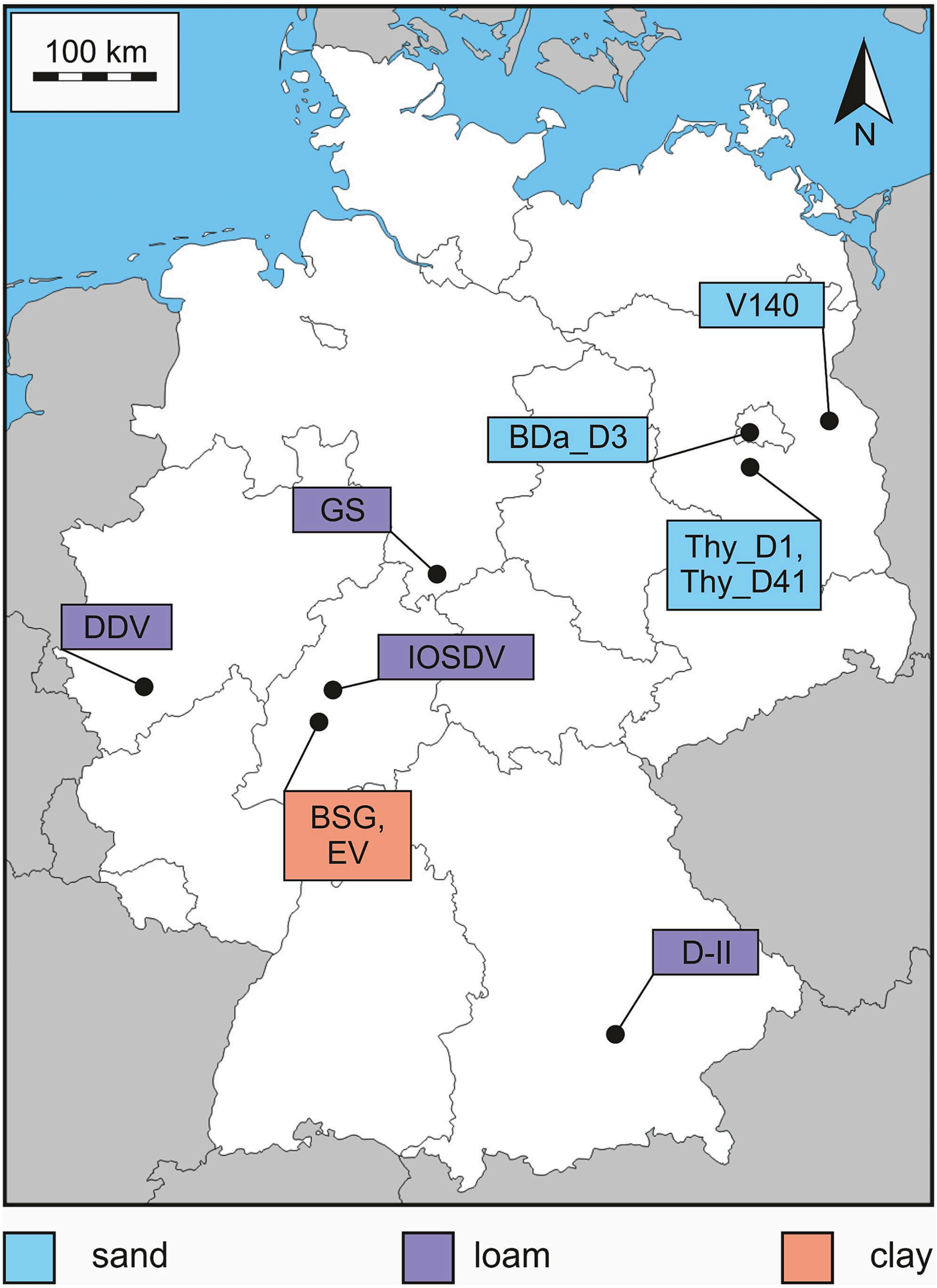

Fig. 1. Map of Germany showing the locations of the long-term experiments (LTE) investigated for soil organic carbon (SOC) stocks, and the dominant soil texture of each site (source: www.d-maps.com). BDa_D3 = static tillage experiment, Berlin-Dahlem; BSG = Biological Nitrogen Fixation Experiment, Gießen; DDV = long-term fertilizer trial Dikopshof, Wesseling; D-II = liming trial Dürnast, Freising-Weihenstephan; EV = Nutrient Depletion Experiment, Gießen; GS = compaction experiment Garte Süd, Göttingen; IOSDV = International Organic Nitrogen Fertilization Experiment, Rauischholzhausen; Thy_D1 = fertilizer and irrigation experiment, Thyrow; Thy_D41 = static nutrient depletion experiment, Thyrow; V140 = fertilization and nutrient gradient experiment, Müncheberg.

managed under conservation tillage, consisting of shallow loosening to 10 cm depth and mulching.

The inclusion of legumes in crop rotation was investigated at BSG with clover and fava bean, which were compared to maize as a control. Maize and fava bean were harvested, whereas clover was incorporated into the soil as a year-round green manure. These three crops were included in a four-fold crop rotation, that is, every four years, fava bean, clover and maize were cultivated (always on the same plot), and crops in the remaining three years were winter wheat, winter rye and spring barley.

Sprinkler irrigation was included as a factor at Thy_D1. Irrigation amounts were adjusted to crop demand under given weather conditions, and ranged between 20 and 484 mm for the years 1971 to 2016 (median 104 mm).

The number of field replicates of the respective treatments differed for the 10 LTEs and ranged from two (DDV) to eight field replicates (V140). Further details, including fertilizer application rates, are listed in Supplementary Table S1.

2.2. Sampling, sample treatment and chemical analyses

The sampling campaigns took place in 2016, 2017 and 2019 during springtime (March–May), except for V140, which was sampled in August 2016. At each plot, 1–3 soil cores were collected down to one meter using a sheath probe core sampler (inner diameter of 60 mm, Nordmeyer Geotool GmbH). All soil cores were cut with a knife at 30 cm depth as the lower boundary for topsoil, irrespective of the actual plowing depth. This chosen depth was based on the German Agricultural Soil Inventory (Poeplau et al., 2020b) and took into account the fact that the average plowing depth in conventional agriculture in Germany is 31 ± 0.1 cm (Schneider and Don, 2019). Additional subdivisions within the topsoil increment were made at 10 cm (GS), 15 cm (BDa_D3), 24 cm (Thy_D1, Thy_D41) or 25 cm (V140, D-II) based on visible changes within the top 30 cm at the respective LTE sites, and SOC was determined separately for upper and lower part of the topsoil. When several cores per plot were collected, the soil material from these cores was pooled and homogenized per depth interval to obtain a composite sample per plot.

Samples were then dried at 40 °C, sieved to 2 mm (referred to as fine soil in the following) and stored for further analysis. Soil moisture was determined on an aliquot of each sample after drying at 105 °C. The bulk density of the fine soil was calculated from the mass of dry soil material (<2 mm) and the volume of the core sampler corresponding to the depth increment.

Total carbon and total nitrogen (TN) contents of the fine soil were measured by dry combustion (EuroEA 3000, HEKAtech, Germany) of a milled aliquot of the samples. Calibration was made against reference measurements of sulfanilamide ($C_6H_8N_2O_2S$, 41.8% C and 16.3 % N) and BBOT ($C_{26}H_{26}N_2O_2S$, 72.5% C and 6.5 % N). All measurements were performed with at least two analytical replicates to ensure that the data reporting had high analytical precision. An additional replicate was measured when the standard deviation between analytical replicates exceeded 0.1% C or 0.05 % N. Soil pH and electrical conductivity were determined in soil suspension (soil:water ratio 1:4). The inorganic carbon content was quantified by calcimetry upon reaction with 4 M HCl (ISO 10693, 1995) and SOC content was calculated as the difference between total and inorganic carbon.

The soil texture was predicted from visible near infrared light reflectance spectroscopy measurements (Hobley and Prater, 2019). The contents in clay, silt and sand were predicted separately using random forest and partial least squares regression models ($R^2 = 0.80–0.95$) and soils from all LTEs were used for model calibration.

Table 1
Overview of sampled long-term experiments, climatic conditions and properties of the sites. BSG = Biological Nitrogen Fixation Experiment, Gießen; DDV = long-term fertilizer trial Dikopshof, Wesseling; Thy_D1 = fertilizer and irrigation experiment, Thyrow; D-II = liming trial Dürnast, Freising-Weihenstephan; BDa_D3 = static soil use experiment, Berlin-Dahlem; Thy_D41 = static nutrient depletion experiment, Thyrow; EV = Nutrient Depletion Experiment, Gießen; GS = compaction experiment Garte Süd, Göttingen; IOSDV = International Organic Nitrogen Fertilization Experiment, Rauischholzhausen; V140 = fertilization and nutrient gradient experiment, Müncheberg. MAT = mean annual temperature, MAP = mean annual precipitation, a.s.l. = above sea level.

Site	GPS coordinates	elevation (m a.s.l.)	MAT [°C]	MAP [mm]	Major soil group (IUSS, 2015)	Texture	Parent material	Start of LTE	Factors of management strategies investigated in present study (with individual starting year, if different from start of LTE)
D-II	48.063° N11.074° E	460	8.4	820	Cambisol	Sandy loam to loam	Cover sand	1978	liming
BSG	50.600° N8.653° E	158	9.0	650	Fluvic Gleyic Cambisol	Silty clay	Floodplain sediments	1982	mineral (N) fertilization pre-crop
EV	50.599° N8.654° E							1954	mineral (N) fertilization
IOSDV	50.761° N8.870° E	235	8.1	595	Luvisol	Silty loam	Alluvial sediments	1984	mineral (N) fertilization organic amendment (FYM, straw)
DDV	50.808° N6.953° E	62	9.7	634	Luvisol	Silty loam	Loess	1904	mineral (NPK) fertilization organic fertilization (FYM) liming
GS	51.488° N9.936° E	150	8.7	645	Luvisol	Clayey loam	Loess	1970	tillage intensity[a]
Thy_D1	52.253° N13.234° E	44	9.2	510	Cutanic Albic Luvisol	Sand	Periglacial sand	1937	mineral (N) fertilization organic amendment (FYM, straw[b]) sprinkler irrigation (since 1969)
Thy_D41	52.252° N13.235° E							1937	mineral (NPK) fertilization liming
BDa_D3	52.467° N13.297° E	51	9.6	540	Luvisol	Loamy sand	Periglacial sand	1923	mineral (P) fertilization organic fertilization (FYM; since 1939) tillage intensity[a] liming
V140	52.517° N14.122° E	62	8.9	532	Albic Luvisol (Arenic, Neocambic)	Silty sand	Aeolian sands over glacial till	1963	mineral (N) fertilization organic amendment (FYM, straw)

a: Tillage intensity refers either to soil inversion (plowing) versus soil loosening (GS) or to contrasting plowing depth (BDa_D3).
b: The site Thy_D1 received FYM from 1938 to 1976 and straw since 1978.

2.3. Calculation of SOC and TN stocks, response ratios and stock change rates

Stocks of SOC (*SOCstock*$_i$, in Mg ha^{-1}) were calculated for the top 30 cm according to Poeplau et al. (2017; Eq. (1)):

$$SOCstock_i = \frac{SOCcont_{finesoil} * mass_{finesoil}}{volume_{sample}} * depth_i \quad (1)$$

where $SOCcont_{finesoil}$ is the SOC content of fine soil (<2 mm) [in mass%], $mass_{finesoil}$ is the mass of fine soil [in g], $volume_{sample}$ is the volume of the sample [in cm^3], and $depth_i$ is the thickness of the regarded depth interval [in cm].

We modified the calculation (Eq. (1)) by including an equivalent soil mass approach (ESM; Wendt and Hauser, 2013) to account for changes in soil bulk density under different treatments, which is necessary for determination of topsoil SOC stocks (Meurer et al., 2018). As the scale basis, the median of the mass of fine earth in 0–30 cm depth ($mass_{finesoilmedian}$) from all plots of the respective LTE was used.

At LTEs where the topsoil was sampled as one depth interval (i = 0–30 cm), the corrected SOC stock was calculated with $mass_{finesoilmedian}$ instead of $mass_{finesoil}$ (Eq. (2)):

$$corrSOCstock_i = \frac{SOCcont_{finesoil} * mass_{finesoilmedian}}{volume_{sample}} * depth_i \quad (2)$$

At LTEs where additional subdivisions were made (Thy_D1, BDa_D3, Thy_D41, V140, GS and D-II), the upper depth increment (i = 0–x cm) was calculated according to Eq. (1). The lower depth increment (i = x–30 cm) was corrected for the difference between the respective $mass_{finesoil}$ and the $mass_{finesoilmedian}$ (Eq. (3), (4)):

$$corrSOCstock_i = \frac{SOCcont_{finesoil} * mass_{finesoil} - mass_{corr}}{volume_{sample}} * depth_i \quad (3)$$

With

$$mass_{corr} = mass_{finesoil0-30cm} - mass_{finesoilmedian} \quad (4)$$

SOC stocks of the upper and lower depth increment were then summed up to obtain total SOC stock for the upper 30 cm.

Stocks of TN were calculated similarly, using Eqs. (1)–(4) with content of TN in fine earth.

Following Bolinder et al. (2020), we calculated *response ratios* (in %; Eq. (5) and *stock change rates* (in kg ha^{-1} yr^{-1}; Eq. (6)) resulting from the various management strategies, against the fully mineral-fertilized ("+NPK") and limed ("+Ca"), not organically amended ("-org"), not irrigated ("-irrigation"), regularly plowed ("regular plow") treatment (yellow bars in Figs. 3–7). A site-adapted mineral fertilization in combination with lime application is part of *Good Agricultural Practices* (e.g., Chien et al., 2009; Vogel et al., 2020), which is why we used this treatment as a reference to calculate stock change rates. This reference treatment was available in all LTEs except for BSG, EV and IOSDV (Supplementary Table S1). These three experiments are located on soils developed in fluvial loam and clay (Table 1), which have a probably high pH-buffering capacity, and where alkaline mineral fertilizers maintained the pH values at an optimal level (Sluijsmans, 1970). Therefore, the respective mineral-fertilized treatments in BSG, EV and IOSDV were considered equivalent to the mineral-fertilized and limed control treatments of DDV, D-II, GS, Thy_D1, BDa_D3, Thy_D41 and V140.

The response ratio and change rates were calculated as follows:

$$response\ ratio = \frac{SOCstock_M - SOCstock_R}{SOCstock_R} * 100 \quad (5)$$

$$stockchangerate = \frac{SOCstock_M - SOCstock_R}{t_s - t_0} \quad (6)$$

With $SOCstock_M$ as the mass-corrected SOC stock of the respective management treatment, $SOCstock_R$ as the mass-corrected SOC stock of the reference treatment, t_s as the sampling year and t_0 as the starting year of the LTE. We also calculated the SOC stock change rate of the unfertilized and non-limed treatments (where available) against the fully mineral fertilized and limed reference, to quantify the effects of omitted fertilization and liming.

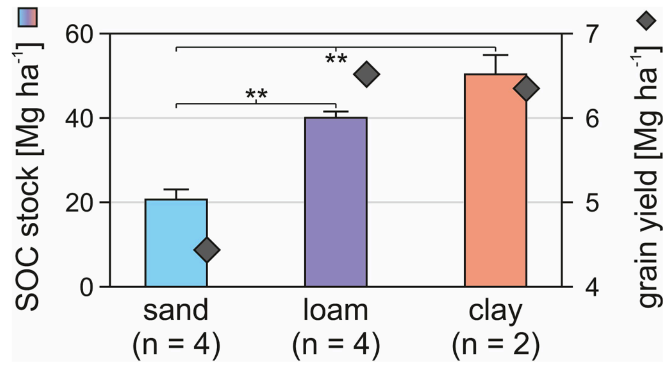

Fig. 2. Soil organic carbon (SOC) stocks in topsoils (0–30 cm) of the LTEs averaged across all treatments (color-coded according to texture groups in Fig. 1) as well as winter wheat grain yields, each sorted by texture. For grain yields, exemplary data from winter wheat are shown to illustrate potential soil texture effects (grain yields do neither correspond directly to the sampled LTEs and treatments nor to years of sampling of the current study). Grain yield data were adapted from mineral-fertilized and limed plots at Thyrow and Berlin-Dahlem (sandy sites; averaged from Thy_D1, treatment N2 -irrig and treatment N2 + irrig, 2010–2015, as well as BDa_D3, treatment conventionally plowed + P + Ca -FYM, 1997–2013), at Dikopshof (loamy site; DDV; years 2015–2016; Ahrends et al., 2018) and at Gießen (clayey site; short-term field experiment for yield and grain investigation; years 2015–2016; Stumpf et al., 2019). The two asterisks indicate significant difference at the $p < 0.01$ level of probability.

Using this calculation method, we assumed that any SOC stock change due to external factors such as climate change occurred in similar magnitude in the managed and control treatments. Hence, differences in SOC stocks between managed and control treatments can still be assigned to the effect of the respective management strategy. We chose this approach because true SOC stocks from the beginning of the LTEs were not available for all sites or because those that were available could not be used reliably due to differing analytical methods for SOC quantification and/or deviating thickness of the investigated depth interval.

The unit kg ha^{-1} yr^{-1} results from dividing absolute SOC stock changes by the duration of management (see Eq. (6)). This simplified calculation does not necessarily mean that there was a linear increase or decrease of SOC stocks over the whole time in the management treatment. We are aware that the assumed linear change of SOC stocks does not necessarily hold true under field conditions; however, this type of reference and this way of calculation enable comparison with previously published studies (Poeplau and Don, 2015; Paustian et al., 2019; Bolinder et al., 2020). In reality, it is more likely that SOC accumulation follows a first-order scenario until a new C equilibrium is reached (van Groenigen et al., 2014). However, the time interval at which this plateau is reached is highly uncertain, and linear trends over several decades have been shown in other studies on topics such as crop rotations (Johnston et al., 2017). Moreover, the steady state might be reached earlier in case of organic fertilization or crop rotation compared to no-till management (Yan et al., 2007), which is a critical point when regarding the effect of combined agricultural measures. The 20-year time span assumed by IPCC (2006) is often too short, as shown, for example, by Poeplau and Don (2015) or Poulton et al. (2018), and there are no data on when this plateau is reached for different textured soils with differences in management practice. Hence, we refrained from

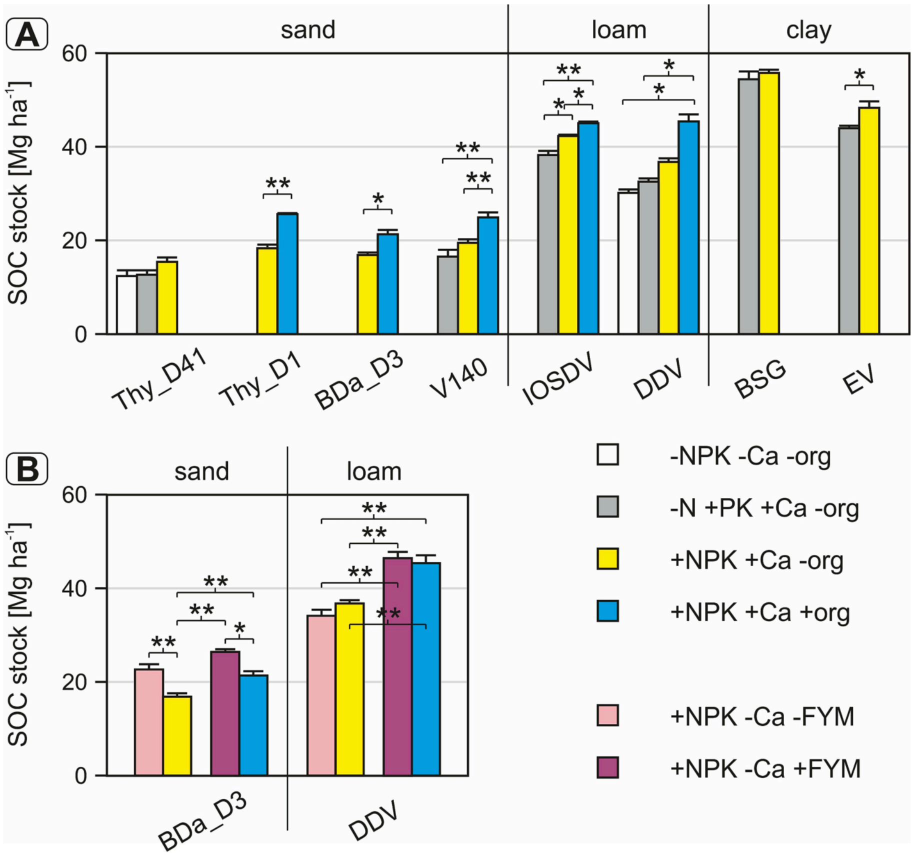

Fig. 3. A) Topsoil (0–30 cm) organic carbon stocks in non-treated (-NPK -Ca -org), not mineral N-fertilized but limed (-N + PK + Ca -org), fully mineral-fertilized and limed (+NPK + Ca -org), as well as of fully mineral- and organically amended and limed treatments (+NPK + Ca + org) of selected LTEs. Note that GS and D-II are not shown here, as both LTEs contain neither a non-fertilized and non-limed treatment nor a mineral-fertilized and organically amended treatment. Treatments with omitted mineral N fertilization are shown instead of completely omitted mineral fertilization because only the former was available in all eight of the LTEs shown here. Blue bars show treatments with FYM application for BDa_D3 and DDV, and treatments with straw incorporation for Thy_D1. For V140 and IOSDV, the blue bars represent the average of all treatments receiving either FYM or straw. B) Topsoil (0–30 cm) organic carbon stocks in fully mineral-fertilized treatments with contrasting FYM application and liming conditions at BDa_D3 and DDV. One asterisk indicates significant difference at the $p < 0.05$ level of probability, two asterisks indicate significant difference at the $p < 0.01$ level of probability.

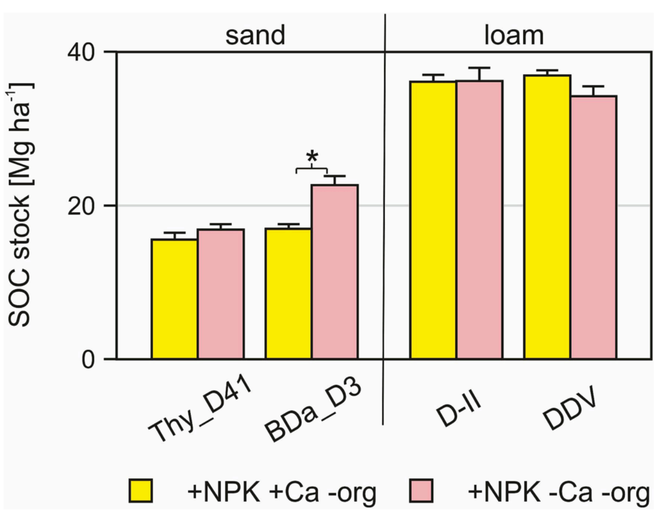

Fig. 4. Topsoil (0–30 cm) organic carbon stocks in limed (+Ca) and non-limed (-Ca) treatments of selected long-term experiments. One asterisk indicates significant difference at the $p < 0.05$ level of probability.

discussing the data solely on the basis of a first-order scenario because we have only a starting and end point to do these calculations, and because simply assuming that a C equilibrium is reached at all sites after 20 years could be incorrect and could lead to false estimations of SOC accumulation rates. As a compromise, we additionally calculated linear SOC stock change rates with a fixed duration of 30 years (see Supplementary Table S2), as numerous studies have shown that the majority of SOC stock change occurs in the first few decades, and thereafter only minor change takes place (Preger et al., 2010); we only comment briefly on potential first-order rate constants in the Discussion Section. When expressing average SOC accumulation in per mille of initial SOC in Section 3.4, these values refer to the whole experiment duration and not to an initial 30-year interval only, where SOC accumulation likely was faster than towards later stages of the LTEs.

By dividing the response ratio by the LTE management duration, an annual average rate of change was calculated and thus can be set into context to the 4‰ threshold, which was provided as an aspirational goal by the soil carbon 4 per mille initiative (Chabbi et al., 2017; Rumpel et al., 2020).

2.4. Presentation of data and statistics

All figures show ESM-corrected SOC and TN stocks. Bar charts show mean values and standard error of the mean (SEM), boxplots show median, interquartile range (IQR), whiskers (minimum and maximum values) and outliers (>1.5-fold IQR).

SOC stocks were tested for normal distribution in each of the three soil textures (sandy, loamy, clayey) via a Jarque-Bera Test. The results showed that transformation of data for statistical analysis was not necessary.

Differences in SOC stocks were then statistically tested between the three soil textures, or between control and management treatment by one-way ANOVA with significance set as probability of error < 0.05 (significant) and < 0.01 (highly significant), respectively, followed by a post hoc Scheffé test using STATISTICA 7.0 (StatSoft).

3. Results and Discussion

3.1. Range of SOC stocks and effect of soil texture

On a plot scale, SOC stocks ranged between 9 and 65 Mg ha^{-1}, with smaller stocks of 20.9 ± 2.3 (SEM) Mg ha^{-1} on average in sandy soils,

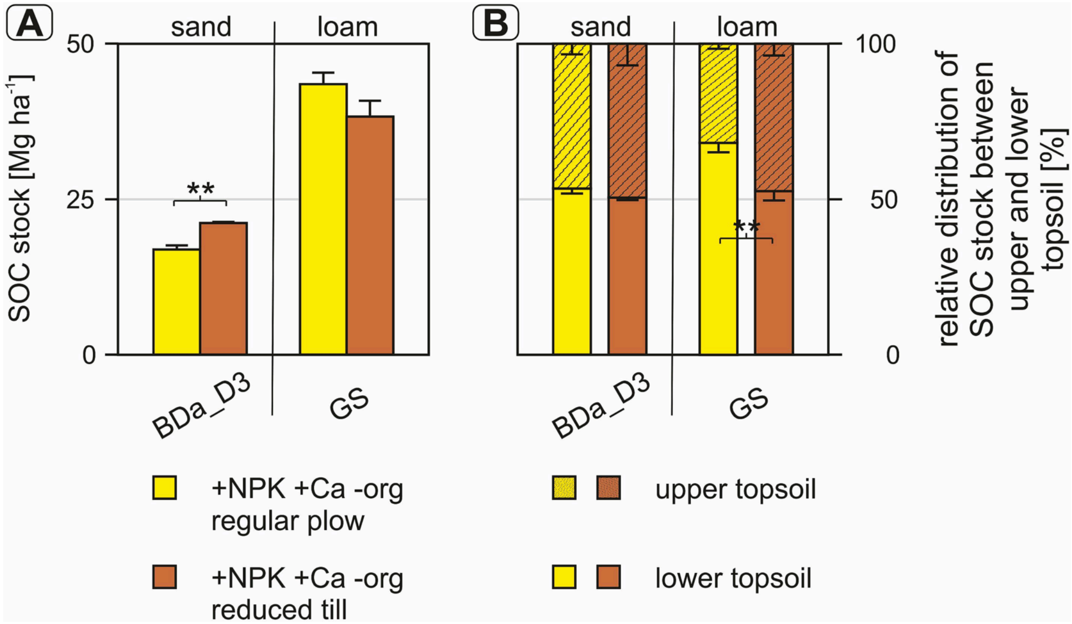

Fig. 5. Topsoil (0–30 cm) organic carbon stocks in conventionally plowed treatments and treatments with reduced tillage. A) absolute values, B) relative distribution of SOC stocks between upper and lower depth increment of topsoil. Note that sampling intervals were 0–15 cm as well as 15–30 cm at BDa_D3, and 0–10 cm as well as 10–30 cm at GS. Two asterisks indicate significant difference at the $p < 0.01$ level of probability.

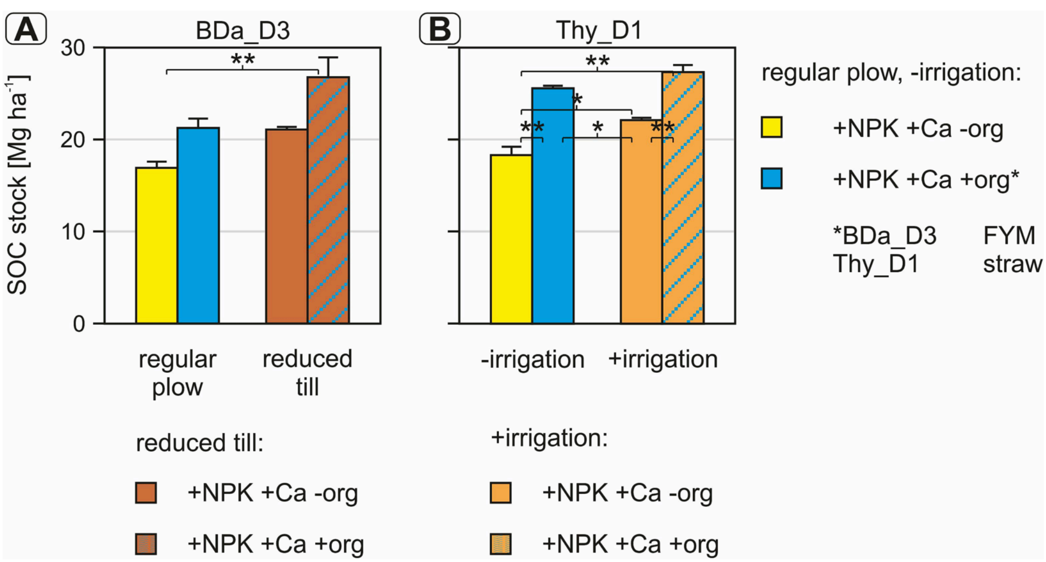

Fig. 6. A) Topsoil (0–30 cm) organic carbon stocks under different tillage (regular plow = 28 cm, reduced till = 17 cm plow) and organic fertilization (FYM) at sandy site BDa_D3. B) Topsoil (0–30 cm) organic carbon stocks under different irrigation and organic amendment (straw) at sandy site Thy_D1. One asterisk indicates significant difference at the $p < 0.05$ level of probability; two asterisks indicate significant difference at the $p < 0.01$ level of probability.

intermediate stocks of 40.1 ± 1.5 Mg ha^{-1} in loamy soils, and highest stocks of 50.4 ± 4.7 Mg ha^{-1} in clayey soils, with sandy sites being highly significantly different from loamy and clayey sites (Fig. 2).

Based on more than 2,500 sites of the German Agricultural Soil Inventory, Vos et al. (2018a) showed that texture is one of the main factors controlling SOC stocks in German arable land.

The increase of SOC stocks with decreasing particle size might be explained in part by higher biomass input into finer-textured soils. As biomass input into the soil via plant residues and root mass correlates with plant growth and biomass, we show respective literature data for crop yields of winter wheat, averaged over 2–16 years, from the experimental stations Thyrow (Thy_D1 and BDa_D3; own data), Dikopshof (Ahrends et al., 2018) and Gießen (Stumpf et al., 2019) as proxies for sandy, loamy and clayey sites, respectively. These grain yields increased significantly from sandy to loamy and clayey sites (Fig. 2). The other reason for higher SOC stocks in loamy and clayey soils is the larger specific surface area provided by clay minerals, giving these soils an elevated storage capacity (e.g., Nichols, 1984). The latter supports organo-mineral associations and physical encrustation in aggregates, which retards SOC turnover due to lower substrate accessibility for microbes (Churchman et al., 2020; Six et al., 2002; Torn et al., 2009). Accordingly, the correlation of SOC stocks with clay contents was significant or highly significant at four of the LTE sites (V140, BDa_3, DDV, BSG; Supplementary Fig. S1), but not within each of the three groups of soil texture ($R^2 < 0.2$; data not shown), despite the rather large variability in clay contents (range 4–16 wt-% for sandy sites, 13–42 wt-% for

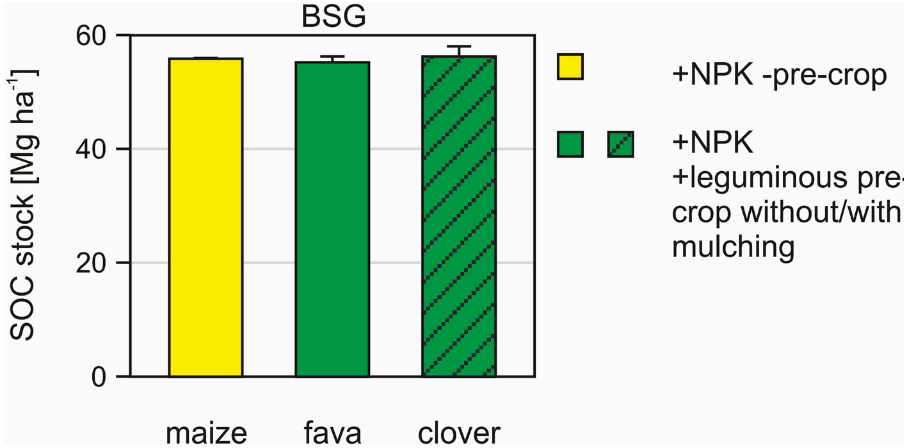

Fig. 7. Topsoil (0–30 cm) organic carbon stocks under different pre-crops at BSG (clayey site).

loamy sites, 23–53 wt-% for clayey sites). It is likely that the combined effects of management and site conditions strongly affected differences in SOC stocks at the German LTEs, as discussed in the following sections.

3.2. SOC stocks under different management strategies

3.2.1. Mineral fertilization and liming

Among the treatments that did not obtain organic fertilization, those receiving full mineral fertilization and liming (i.e., reference treatment) contained the highest topsoil SOC stocks, whereas nutrient deficit, by omission of either nitrogen or NPK fertilization, together with omission of liming decreased SOC stocks (Fig. 3A). The SOC loss from the reference treatment to the limed treatment without mineral N fertilization ranged between 1.3 and 4.5 Mg ha^{-1} (response ratios [RR] −2.3 to −18.8%; Supplementary Table S2), was highest for loamy sites (IOSDV, DDV) and clayey site EV and lowest for clayey site BSG, and was significant or even highly significant at most sites, except for Thy_D41 ($p = 0.075$) and BSG ($p = 0.441$). The decrease from the reference treatment to the treatment without mineral fertilization and liming was even larger, again with largest absolute SOC loss at a loamy site (DDV: 6.7 Mg ha^{-1}, RR −18.2%) and lower SOC loss at a sandy site (Thy_D41: 3.2 Mg ha^{-1}, RR −20.5%).

One explanation for the strong positive association between nutrient application and SOC storage is that nutrient application by mineral fertilization increases OC input to the soil by increasing primary production (Gregorich et al., 1996; Halvorson et al., 1999; Ladha et al., 2011). In particular, N fertilization has been shown to control SOC storage (e.g., Oldfield et al., 2019). After prolonged management, SOC stocks increased approximately linearly at nearly all sites with increasing soil TN stocks (Supplementary Fig. S2A–C), although this relationship weakened or even disappeared towards or above total N and SOC stocks of 6 Mg TN and 60 Mg SOC ha^{-1}, respectively (Supplementary Fig. S2C). The latter might be site-specific and requires further research. The slopes of the relationships between TN and SOC reflect the soil C:N ratios, which averaged between 9.1 and 11.5 at the different sites (Supplementary Fig. S2A–C). This is lower than an exemplary C:N ratio of around 12 for arable soils mentioned by van Groenigen et al. (2014) and at the lower margin of the average C:N ratio of 11.2 obtained from the German Soil Inventory Agriculture (Schneider et al., 2021), but generally supports the authors' idea that sequestering SOC is only possible when N can also be stored in soil in a fairly constant C:N ratio. Agricultural management options hardly changed this ratio even in the long-term. Our data show that the underlying controls are site-specific, but support the general need to adapt N fertilization to plant demand, not only for optimizing yields, but also in terms of climate change mitigation (Amelung et al., 2020).

Intriguingly, no significant changes in SOC stocks were observed under increasing levels of N (IOSDV) or NPK fertilization (V140) above 100 kg N ha^{-1} yr^{-1} and 86 kg N ha^{-1} yr^{-1}, respectively, unless combined with organic fertilization (FYM; Supplementary Fig. S3). One reason for this could be that these N fertilization rates were, at these specific sites, already in the upper range for the possible SOC accrual, which meant that the additional application of organic fertilizer (FYM) could lead to additional SOC accrual.

The addition of lime to the non-fertilized trials (white bars in Fig. 3A) did not result in a significant SOC gain, even if an incomplete mineral fertilization (P and K) was applied together with lime (gray bars in Fig. 3A). Also, under full mineral fertilization, no (site DDV) or even negative effects (site BDa_D3) of liming on SOC accrual were observed (pink and yellow bars in Fig. 3B). The specific effect of liming on SOC stocks, under full mineral fertilization, was summarized in Fig. 4. At both sandy sites (BDa_D3, Thy_D41), omission of liming increased SOC stocks by 5.7 Mg ha^{-1} and 1.3 Mg ha^{-1}, respectively (RR 33.5% and 8.0%), whereas at the loamy sites it had either no effect (D-II) or slightly decreased SOC stocks by 2.7 Mg ha^{-1} (DDV, RR −7.4%).

These findings reflect the complex effects of lime application. On one hand, liming acidic soils promotes primary production and thus leads to higher OC input into soil as long as the shoot:root ratio remains constant; it also has positive effects on soil structure, leading to improved physical protection of SOM (Haynes and Naidu, 1998; Rowley et al., 2018). On the other hand, increased pH values resulting from liming may favor SOM mineralization due to increased microbial activity (Haynes and Swift, 1988), particularly in sandy soils, which usually have lower pH than loamy or clayey soils (Frank et al., 2019). In a global *meta*-analysis, Wang et al. (2021) showed the highest average soil respiration by liming in soils with coarse texture and lowest soil respiration by liming in soils with fine texture. The authors further showed that potential relative SOC gain by liming was highest in medium texture soils, and lower, including also negative SOC changes, in coarse soils, although the range for both texture groups was rather large. Besides soil texture, the effect of liming on net SOC loss or gain is affected by climate, management practice and biomass return (Inagaki et al., 2017; Paradelo et al., 2015). Texture and climate might explain the different responses of SOC to liming in the current study to some extent, as mean annual precipitation at both sandy sites was in the lower range, and at both loamy sites in the upper range of the LTEs investigated here. On one hand, the beneficial effects of liming on soil structure require a certain minimum clay content for flocculation (Beetham, 2015; Paradelo et al., 2015), which was unlikely to be reached at the sandy sites that had clay contents < 10 wt-% (data not shown here), and were additionally allocated in regions with low annual precipitation (see Table 1). On the other hand, especially in non-calcareous soils, liming can significantly increase crop yields due to improved growth conditions. Therefore, application of lime is regarded as an important agricultural measure, if the resulting SOC loss can be compensated by other management techniques such as organic fertilization (see Section 3.2.2.1).

3.2.2. Organic amendments

Similar to mineral fertilization, organic amendments increased SOC stocks significantly or even highly significantly at sandy and at loamy sites (Fig. 3A), with a surplus compared to the reference treatment between 2.7 Mg ha^{-1} and 8.7 Mg ha^{-1} (RR 6.4 to 39.6%). These SOC gains were in the same range as those from the reference treatment (+NPK + Ca; see Section 3.2.1) compared to the untreated plots (-NPK -Ca). Intriguingly, both the highest (site DDV) and the lowest (site IOSDV) SOC gains by organic amendments occurred at loamy sites.

In contrast to mineral fertilization, organic amendments increase OC input to the soil, not only by improving yields and root biomass in case of manure (Chirinda et al., 2012), but also by directly adding carbon derived from external sources, including both manure and plant residues (Han et al., 2016). This is why the effect of mineral fertilization on SOC gain can be enhanced by additional application of organic amendments (Gross and Glaser, 2021). Also, other studies found a net SOC loss in mineral-fertilized soils with reduced or even no organic amendments (e.g., Dalal et al., 2011; Menšík et al., 2018). These findings cannot be directly compared to ours as we did not compare the SOC stocks to the initial stock of each LTE, but instead related SOC stocks to the reference treatment. Nevertheless, the findings of the mentioned studies point in the same direction as our results.

The application of either straw or FYM (the latter usually contains straw at variable amounts) increased SOC stocks to a similar extent (3.4–8.7 Mg ha^{-1} and 2.3–7.3 Mg ha^{-1}, RR 8.0 to 32.4% and 5.4 to 39.6%, respectively; Supplementary Table S2). However, at the LTEs comprising treatments with either FYM or straw, FYM application always yielded higher SOC gain than did straw incorporation alone (V140: 6.3 vs. 3.8 Mg ha^{-1}, RR 32.4 vs. 19.6%, IOSDV: 3.4 vs. 2.3 Mg ha^{-1}, RR 8.0 vs. 5.4%; for all data see Supplementary Table S2). At IOSDV, the difference between FYM and straw treatments was quite small, although straw was added with considerably lower rates than FYM, likely as a consequence of higher doses of mineral fertilizer in the straw treatments (see Supplementary Table S1).

Farmyard manure application was also estimated to have a stronger effect than straw incorporation in global *meta*-analyses (Han et al., 2016) and by modeling (Vleeshouwers and Verhagen, 2002). Accordingly, in their compilation of 20 German LTEs, Körschens et al. (2012) observed that SOC accumulation under straw incorporation reached only 60% of that found under FYM application, which was attributed to higher portion of easily degradable C in straw compared to FYM (Joschko et al., 2015). Also, in a dryland maize rotation, higher SOC gain was observed with FYM than with straw (Liu et al., 2013), mainly due to the higher degree of transformation of FYM compared to straw. The loss of easily available C fractions in manure reduces its decomposition in soils, which promotes long-term SOC accumulation. Findings from a British LTE close to Rothamsted support this observation: Chater and Gasser (1970) found that FYM application preserved the level of SOC contents over 27 years, whereas straw application did not prevent SOC loss, even if this loss was lower than in treatments without straw application. Moreover, Drinkwater et al. (1998) suggested that organic amendments with a narrow C:N ratio, such as FYM (20:1 – 30:1), have a longer retention in soil than materials with a wide C:N ratio like straw (up to 100:1), although a wider C:N ratio does not automatically favor decomposition. Nevertheless, we did not observe a significant change of soil C:N ratios by either FYM or straw application at sites V140 and IOSDV (V140: $p = 0.556$–0.982; IOSDV: $p = 0.098$–0.827; Supplementary Fig. S2A, B), which indirectly confirms the fact that C:N ratios of soils globally move towards 12 (Batjes, 1996).

Despite the possible advantages of FYM in terms of SOC gain and also N supply to crops – leading to higher OC input to soil – Triberti et al. (2008) emphasized that straw incorporation should be preferred over FYM and slurry application if these organic amendments are unavailable on-site, as the latter release carbon (CO_2 and CH_4) via decomposition during storage, which negatively affects the overall C balance on an ecosystem level. In addition, as long as the manure was not originally planned to be landfilled or combusted, using FYM for C accrual at a given site frequently involves a lack of C accrual at another site, which does not receive this FYM. Due to such so-called C leakage, the overall effects of FYM for global C sequestration in soils may be zero, or at least lower than assumed from elevated SOC stocks (Amelung et al., 2020; Paustian et al., 2019; Tiefenbacher et al., 2021). However, such farm-level and regional scale factors were beyond the scope of our study.

3.2.2.1. Combination of FYM application with liming. Similar to the limed treatments (see Section 3.2.2), SOC stocks increased with organic fertilization (FYM) in the non-limed treatments as well, at site BDa_D3 from 22.7 ± 1.1 to 26.4 ± 0.5 Mg ha^{-1} and at site DDV significantly from 34.1 ± 1.3 to 46.5 ± 1.3 Mg ha^{-1} (pink and violet bars in Fig. 3B). Conversely, the joint use of liming and organic fertilization (blue bars in Fig. 3B) led to a significant SOC loss at site BDa_D3 compared with organic fertilization alone (violet bars in Fig. 3B). Our findings can be reconciled with a previous study on a loamy soil under temperate climate, where combined liming and FYM application yielded lower SOC gain than FYM alone (Jokubauskaite et al., 2015).

3.2.3. Tillage

At the sandy site (BDa_D3), long-term reduction of plowing depth to 17 cm instead of 28 cm led to significantly higher SOC stocks in the upper 30 cm of soil by 4.2 Mg ha^{-1} (Fig. 5A; RR 24.8%). At the loamy site (GS), by contrast, SOC stocks were not significantly affected by reduced tillage and mulching (RR −12.1%; difference not significant). Therefore, we were not able to confirm a previous study by (Heinze et al. (2010), who found significantly higher SOC stocks in 0–30 cm depth under reduced tillage than under conventional tillage at GS and one other LTE (Hohes Feld) near Göttingen. Instead, we suggest a texture-(and maybe climate-) dependent interaction with tillage on SOC stocks.

For temperate regions, the possible SOC stock gain by intermediate-intensity tillage versus high-intensity tillage (such as shallow loosening versus conventional plowing at site GS) was determined by Haddaway et al. (2017) as + 1.7 Mg ha^{-1}, which is lower than potential SOC stock gains by no tillage versus high-intensity tillage or no tillage versus intermediate-intensity tillage. Further, the authors found a more positive response of loamy sandy soils than other soil texture types on intermediate- versus high-intensity tillage, and the significant SOC stock gain at BDa_D3 by reduced depth of soil inversion points to a similar direction. However, a detailed comparison of our results with the mentioned review was not possible due to missing data on the respective soil classes loamy sand (BDa_D3) and clay loam (GS), as well as on different plowing depths within the category high-intensity tillage (as is the case at site BDa_D3).

Aggregate disruption by tillage can be a major cause of C loss in arable soil (Smith, 2008) as the increased soil aeration promotes aerobic decomposition processes. Hence, in the long-term, minimum tillage can lead to an improved soil structure and thus stronger protection of SOC over the entire sampling depth of 30 cm (Cui et al., 2014). This effect contrasts with high concentrations of SOC being restricted to shallower depths, with possibly elevated decomposition rates in the near surface soil. Here, the data for the sandy site (with soil inversion in both variants; BDa_D3) confirmed that SOC accrual in the topsoil by reduced tillage is possible. In contrast, contrary to our expectations, the positive effect of reduced tillage on SOC stocks was absent at the loamy site (GS), despite the stronger contrast between the variants (non-inversion versus inversion of soil).

Interestingly, the reason for this absent SOC gain at site GS was not the higher decomposition near the soil surface under reduced tillage, as SOC stocks increased from 13.9 ± 0.7 to 18.1 ± 1.4 Mg ha^{-1} in 0–10 cm depth (i.e., a highly significant relative gain of ∼ 15% in upper topsoil;

Fig. 5B). This is in agreement with findings by Haddaway et al. (2017) that, under reduced tillage, loamy soils in particular benefit in terms of SOC storage in 0–15 cm depth. Rather, the absent overall SOC gain at GS resulted from the strong decrease of SOC stocks at 10–30 cm soil depth from 29.6 ± 1.3 Mg ha^{-1} in the conventionally plowed treatment to 20.2 ± 1.1 Mg ha^{-1} in the treatment with loosening and mulching (data not shown). Heinze et al. (2010) observed the same for SOC contents and this might be explained, amongst others, by altered root growth and microbial community.

In contrast, at site BDa_D3, SOC stocks below the shallow plowing depth (15–30 cm depth) remained almost constant under both tillage treatments, with approximately 10 Mg ha^{-1} (data not shown).

3.2.3.1. Combination of tillage with liming. The gain in SOC by reduced tillage was enhanced by liming at the sandy site BDa_D3, resulting in a gain of 4.2 Mg SOC ha^{-1}, which is 1.6 Mg SOC ha^{-1} more than in the non-limed treatments with reduced versus conventional tillage.

This means that a reduced plowing depth could outweigh the negative effect of liming on SOC stocks. These findings concur with other studies showing that complete exclusion of tillage directly after liming helps to sustain the positive effects of liming on soil structure and SOC stocks, which fosters SOC stabilization (Frank et al., 2019; Inagaki et al., 2017). The largest SOC stock gain was detected when comparing the non-limed, shallow plowed treatment to the limed and conventionally plowed treatment (+8.3 Mg ha^{-1}, RR 49.0%; Supplementary Table S2).

3.2.3.2. Combination of tillage with FYM application. At the sandy site BDa_D3, with application of FYM, SOC stocks were higher by 5.5 Mg ha^{-1} in shallow plowed than in conventionally plowed treatments. The magnitude of the increase tended to be larger than in treatments without FYM application (4.2 Mg ha^{-1}; Fig. 6A), although the difference itself was not significant ($p = 0.070$). This may have been a site-specific effect. In general, conventional plowing leads to better incorporation of organic material into soil than shallow plowing, which fosters SOC accrual due to lower overall mineralization rates of the organic materials added (Chenu et al., 2019; Mary et al., 2020). Here, the site BDa_D3 is also prone to summer drought, so the effects of enhanced mineralization in shallow tilled surface soil might be less prominent than in other studies that have been performed under wetter climates. In any case, the joint consideration of our data with those reported by others clearly shows that management effects on SOC stocks do not depend on a single measure, but are controlled by a multiple range of management interactions.

3.2.4. *Irrigation*

Arable soils in NE Germany, as presented by site Thy_D1, are prone to drought during summer. Hence, irrigation trials have been established, and in this LTE, irrigation increased the SOC stocks significantly by 3.8 Mg ha^{-1} (yellow and orange bars in Fig. 6B), corresponding to a RR of 20.7%.

This positive effect of irrigation on SOC accrual can be attributed to increased primary production, and thus increased aboveground and root biomass input to soil (Trost et al., 2013; Zhou et al., 2016), which apparently even outbalances the enhancement of SOC mineralization by irrigation (Chenu et al., 2019) at the investigated site. Our data agree with findings by Trost et al. (2013) that irrigation increases SOC accrual particularly under drier climates and when initial SOC stocks are low, as is the case at the site Thy_D1.

3.2.4.1. Combination of irrigation with straw incorporation. At Thy_D1, the SOC stock gain resulting from irrigation was not significant regarding plots with straw incorporation (25.6 ± 0.2 Mg ha^{-1} in non-irrigated treatment versus 27.3 ± 0.8 Mg ha^{-1} in irrigated treatment; blue and brown-blue bars in Fig. 6B; $p = 0.100$). In contrast, combination of irrigation and straw incorporation yielded highest SOC stocks throughout the LTE of 27.4 ± 0.8 Mg ha^{-1}, thus exceeding the SOC stocks in the non-irrigated and not organically amended treatment still by 9 Mg SOC ha^{-1} (Fig. 6B; RR 49.0%; Supplementary Table S2).

These findings indicate that, at sandy sites, organic amendments and irrigation effects add up for SOC accrual, even if the former has the larger effect on SOC accrual. This is likely due to the unidirectional input of OM by organic amendments in contrast to the bidirectional effect of irrigation, which increases biomass input but also enhances SOC mineralization (Chenu et al., 2019; Trost et al., 2013). It is likely that site heterogeneities impeded the detection of significant changes at Thy_D1.

3.2.5. *Pre-crops*

Apart from the technical means of improving soil conditions, the use of suitable crop rotation may also improve soil fertility and subsequent SOC gain by management. At the site BSG, the use of clover tended to result in larger SOC stocks than just using maize in the control plots, but the difference was small (0.4 Mg ha^{-1}; RR 0.7%) and not significant ($p = 0.855$; Fig. 7). Fava bean as pre-crop did not increase SOC stocks at all, reflecting that grain harvest of both fava bean or maize corresponded to a C output, while C input as residue return from straw of maize was greater than that from fava. This likely led to a diminishment of the differences between maize and fava bean treatment, in contrast to clover treatments where complete plant biomass was incorporated into soil. The rather large error bars of both pre-crop treatments compared to those of the control treatment show that the variation in SOC levels between plots might still exceed any effects of the pre-crop on SOC gain. Thus, pre-crops had a considerably smaller effect on SOC accrual at BSG than mineral N fertilization, for instance (1.3 Mg ha^{-1} compared to the treatment without mineral N fertilization). Accordingly, we were not able to confirm the general expectation of highest SOC accumulation rates under clover, which has been attributed to the nitrogen fixation effect of leguminous pre-crops in general (Autret et al., 2016; Christopher and Lal, 2007; Poeplau and Don, 2015), or to the additional OC input by green manure in the clover treatments. Also, the C:N ratio did not differ significantly between the control treatment and the two pre-crop treatments at site BSG ($p = 0.378$–0.975; Supplementary Fig. S2c), although leguminous pre-crops commonly bear a much lower C:N ratio than non-leguminous crops.

Hobley et al. (2018) demonstrated that the choice of pre-crop alone did not lead to differences in SOC storage at BSG top- and subsoil, whereas under N deficiency, clover as a pre-crop caused a significant SOC gain not only in topsoil, but also down to a depth of 50 cm.

The pre-crops at BSG were cultivated only every fourth year; this means that, after an experiment duration of 34 years, the LTE had passed through nine crop rotations. Further, the last year with pre-crop cultivation was three years prior to sampling; this, together with the above-mentioned effect of grain harvest in maize and fava bean, could have impeded the detection of significant SOC stock changes by leguminous pre-crops.

3.3. *Effects of management duration, clay content and reference SOC stocks on response ratios*

The above-mentioned findings show that management effects on SOC accrual interacted at a given site, with additional differences between sandy and clayey sites and therewith between sites of drier climate in NE Germany and a wetter one in W and SW Germany. In order to generalize these findings, we must also consider that the response ratio has been calculated solely on the basis of SOC stocks, not considering LTE duration (Eq. (5)). Relating the RR to the LTE duration revealed a strong scattering due to above-mentioned interactions of management on SOC accrual. However, it also revealed a tendency of increasing RR values over time in both directions, for positive RR values (organic amendments, irrigation, no liming at sandy sites; significant correlation; $R^2 = 0.39$; $p = 0.04$), as well as for the negative ones (no N or NPK fertilization at all sites, no liming at loamy sites; Fig. 8A),

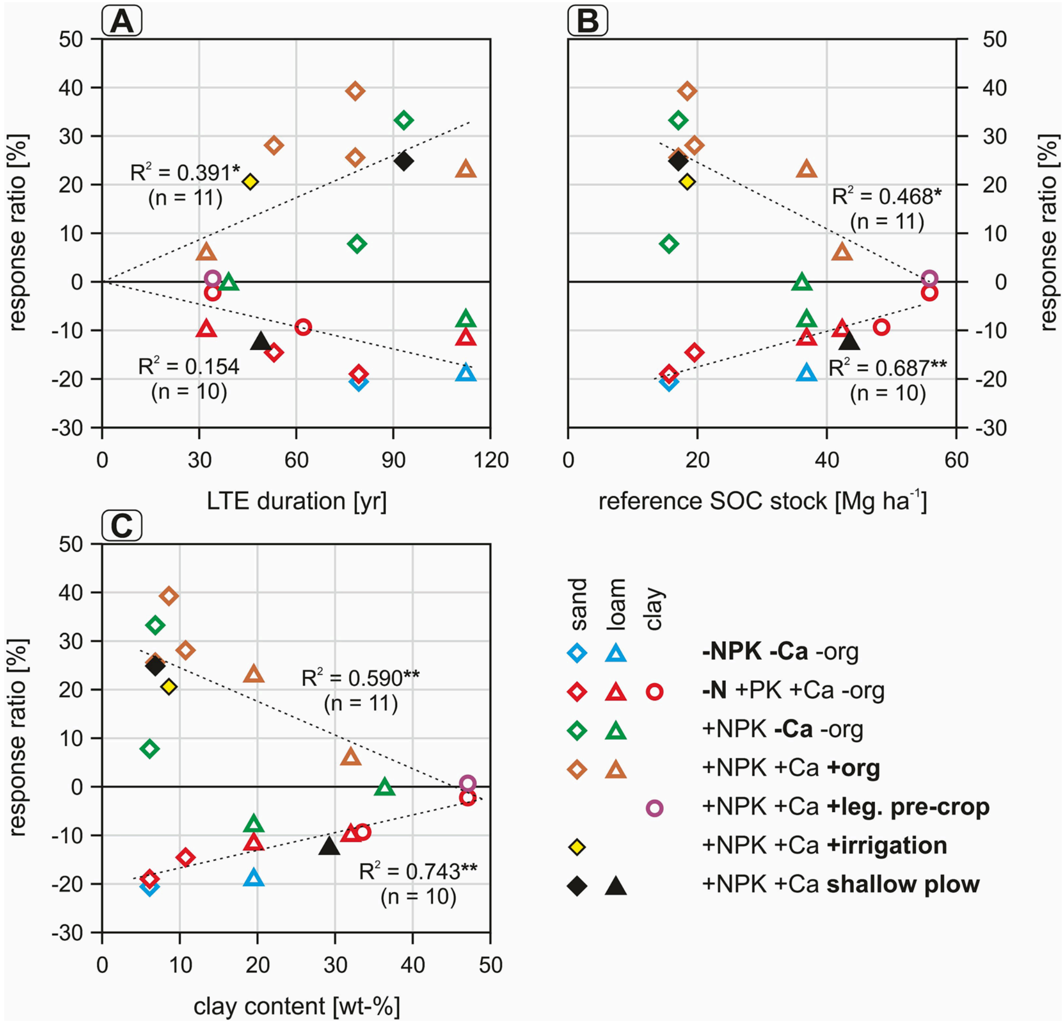

Fig. 8. Crossplots of response ratio (RR) of SOC stocks in topsoils (0–30 cm) relative to the management under Good Agricultural Practice, i.e., fully mineral-fertilized plots with liming versus A) LTE duration in years, B) SOC stocks of reference treatment in Mg ha^{-1}, which were considered here as "initial" SOC stocks for lack of real initial SOC stocks, and C) clay content in wt-% (averaged over all treatments for each LTE). Dashed lines represent trend lines, determined separately for positive and negative RR in each crossplot. Note that trend lines are connected to the axes' center point in Fig. 8A because it is assumed that management treatment and reference treatment had identical SOC stocks at the beginning, and thus RR at the starting point was zero. The diagrams show only single agricultural measures, but not combinations thereof. In the legend, those factors of management that deviate from the conditions of Good Agricultural Practice (i.e., mineral fertilization and liming) are written in bold letters. Brown symbols represent the average of all treatments receiving either FYM or straw in case of those LTEs where both types of treatments existed (V140, IOSDV). One asterisk after the coefficient of determination indicates significance of the correlation at the $p < 0.05$ level of probability; two asterisks indicate significance of the correlation at the $p < 0.01$ level of probability.

because the ongoing differentiation of SOC between treatments is a result of long-term accumulation effects. The diagram further indicates that application of organic amendments (FYM, straw) leads to a SOC gain that can be approximately twice as high as the potential SOC loss by omitted N or NPK fertilization.

When relating RR to reference SOC stocks (see also Section 2.3; Fig. 8B), or to clay contents (Fig. 8C), similar to Bolinder et al. (2020), the largest SOC gains were observed for sites with low reference SOC stocks, and thus highest sand and lowest clay content, while effect sizes declined with higher reference SOC stock and higher clay content ($R^2 =$ 0.47 to 0.74; Fig. 8). As clay contents and reference SOC stocks were significantly correlated to each other ($R^2 = 0.90$; $p < 0.01$; data not shown), the individual effects cannot be separated; nevertheless, they provide additional evidence that there were not only interactions among the different management effects as outlined above, but also between management and site properties. There were also weak negative correlations between LTE duration and clay content, as well as between LTE duration and reference SOC stocks in our data set, although only the former of both was significant ($R^2 = 0.479$, $p = 0.03$; $R^2 = 0.275$, $p =$ 0.12; data not shown).

In their global *meta*-analysis of SOC stock changes, Bolinder et al. (2020) tried to examine, among other things, the interacting effects of texture and initial SOC on SOC stock changes under various agricultural measures. For texture, they found ambiguous results, whereas for initial SOC stocks, they reported from several studies that RR for straw application decreased with increasing initial SOC stocks (e.g., Liu et al., 2014; Minasny et al., 2017). The latter is supported by the findings of the current study if considering the reference SOC stock as "initial" SOC stock (see Section 2.3), meaning that those sites with lowest SOC stocks in general (i.e., sandy sites), exhibit the highest potential for large SOC stock changes by various agricultural management techniques.

3.4. Relative SOC stock change rates

The relative SOC stock change rates at all sites ranged between −3.0 ‰ yr^{-1} and + 10.6 ‰ yr^{-1}, where negative rates were restricted to treatments that received no mineral fertilization or no mineral N fertilization (independent of dominant texture), as well as to reduced tillage and omission of liming at loamy sites. Generally, the highest and most positive rates of SOC stock changes were observed at sandy sites, which also are the driest sites (Fig. 9, Table 1). The maximum rates of annual SOC accrual even exceeded the 4 ‰ symbolic figure aspired to by the 4 per mille initiative in many cases, albeit only with organic amendments or without liming at sandy sites, combined with reduced tillage or irrigation. Recently, Roß et al. (2022) also showed for another LTE at the sandy site Thyrow, that SOC accumulation by FYM application of far more than 4 ‰ yr^{-1} is possible. These results support the statement by Minasny et al. (2017) who claimed that the highest SOC accumulation can be reached in soils with low initial topsoil SOC stocks (<30 Mg ha^{-1}), as is the case here for sandy cropland soils. For treatments receiving organic amendments, there is a risk that these effects are prone to C leakage, that is there is no real SOC accrual at larger scale as the added fertilizer C represents a loss of C input at the sites from which the organic matter was removed (Amelung et al., 2020), although this depends on alternative uses of the organic materials (Lessmann et al., 2022; see Section 3.2.2).

At loamy sites, FYM application without liming was most effective in increasing SOC stocks. On average, the investigated agricultural management strategies yielded the lowest positive SOC stock change rates at clayey sites, although these already had the largest SOC stocks among the LTEs under study.

Post and Kwon (2000) summarized the main drivers of SOC loss from arable soil as (i) reduced organic matter input to the soil, (ii) decreased stability of plant residues and (iii) a lack of physical protection due to intensified tillage. While the analysis of SOC pools of different stability, as recommended by Vos et al. (2018b), was not the aim of our study, we can clearly confirm points (i) and (iii) by inverse observation: application of organic amendments increased SOC stocks by up to ca. 6 ‰ yr^{-1}, while reduced tillage increased SOC stocks at least at the sandy site by almost 3 ‰ yr^{-1}.

Despite such positive effects on SOC accrual, our SOC accrual rates found for German LTEs were one order of magnitude lower than SOC sequestration rates estimated by Lal (2008) for the best management practices in Europe, or those compiled by Minasny et al. (2017) from a global literature set. Nevertheless, the upper limit of the relative SOC accrual rates in German LTEs agrees with the upper limits reported earlier (e.g., up to 7.1 ‰ yr^{-1}, by animal manure; Smith et al., 2000), and suggests that SOC accrual rates of up to 10 ‰ yr^{-1} could be reached for arable topsoils with low initial SOC stocks (≤30 Mg ha^{-1}; Minasny et al., 2017) but not on a large scale.

The calculation of relative SOC stock change rates allows a comparison with the aspirational goals of the 4 per mille initiative. Nevertheless, any rise of SOC that is expressed in per mille of former SOC stock cannot proceed forever, because this would imply a non-linear, endless increase of C stocks rather than a logarithmic or restricted exponential growth to a maximum. If calculating the latter from our two available data points only, we would have to rely on certain assumptions, such as time-invariant initial C content of the control, as well as the occurrence of a plateau in stock change rates that is reached simultaneously at all sites, which is unlikely to be true (Yan et al., 2007), and which may occur after more than 20 years, as suggested by IPCC (2006) (Poeplau and Don, 2015; Poulton et al., 2018). Given the lack of data to support these assumptions, we only present linear accumulation scenarios, although it is likely that these represent a strong simplification of natural processes in the field.

3.5. Carbon balance at the ecosystem level and outlook

Although there are benefits of organic amendments in terms of SOC accrual, disadvantages such as increased nutrient leaching due to manure application must be considered (Vanden Nest et al., 2016). To reduce these risks, precision farming that includes spatially adapted spreading of manure according to fertilizer needs (Jarecki and Lal, 2003; Leenen et al., 2019), use of stabilized organic materials like compost (Molina-Herrera and Romanyà, 2015), biochar use, or preferred cultivation of deep-rooting, lignin-rich plants (Amelung et al., 2020; Kell, 2012; Paustian et al., 2019; Poeplau et al., 2021) may be recommended. Another option could be to replace silage maize by grass-clover mixture

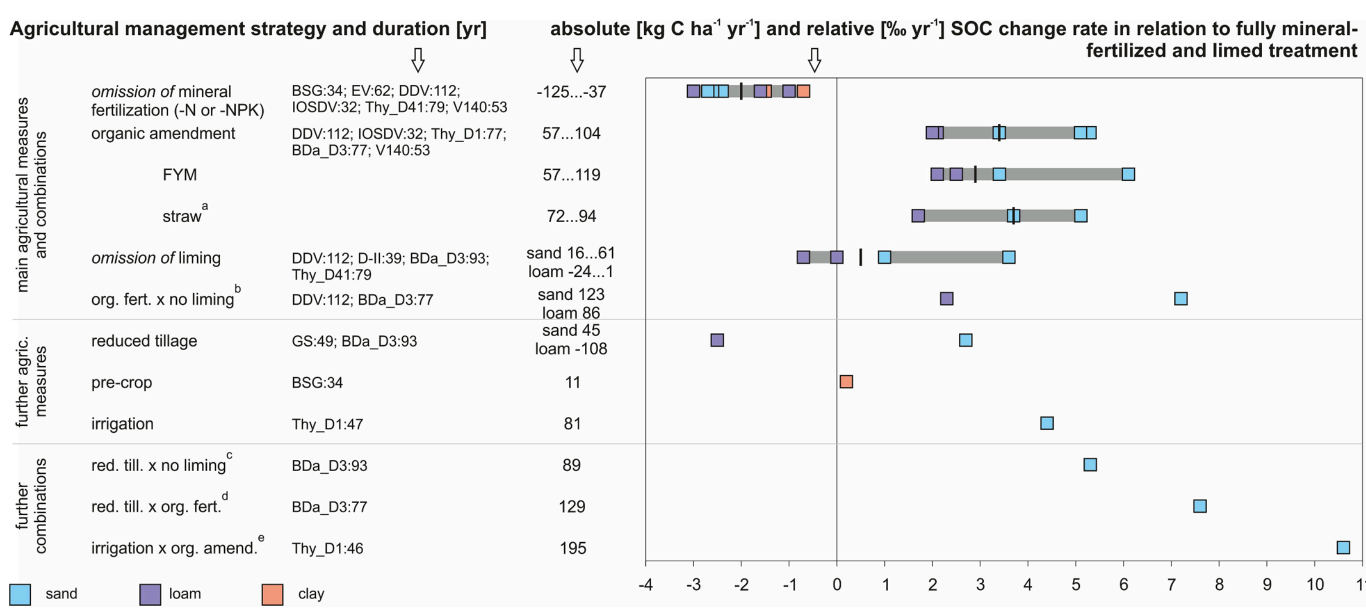

Fig. 9. Absolute and percental soil organic carbon (SOC) change rates in topsoil (0–30 cm) under the respective agricultural management techniques or, as in case of mineral fertilization and liming, omission of these. Reference treatment for all presented rates was the treatment with GAP conditions (mineral-fertilized, limed; not organically amended, not irrigated, conventionally plowed). Here, SOC change rates were calculated using the real duration of the LTE or treatment, while SOC change rates calculated with a fixed duration of 30 years are shown in the Supplementary Material. Grey bars show the total range of the respective rates; black lines within these, where applicable, represent the median. Please note that Thy_D1 is listed here as a site with straw application, although it received FYM during the first 38 years (see also Table 1). a: includes mixture straw + mineral N + winter rape as catch crop at IOSDV. b: +FYM -liming versus -FYM + liming. c: shallow plowing depth -liming versus regular plowing depth + liming. d: shallow plowing depth + FYM versus regular plowing depth –FYM.: +sprinkler irrigation + straw application versus -sprinkler irrigation -straw application.

in animal husbandry, although farmers prefer maize because it is simpler to grow. A full climate balance should also consider offsite and non-CO_2 greenhouse gas emissions, such as nitrous oxide (Li et al., 2005), in a life cycle assessment and a monitoring of deeper subsoil (Skadell et al., 2023). Nonetheless, our data clearly show that topsoil SOC gains with agricultural management can be substantial, with the potential to contribute significantly to climate change mitigation (Bai et al., 2019; Lessman et al., 2022).

4. Conclusions

We estimated absolute and relative rates of SOC stock change in German arable soil under common long-term conventional agricultural management techniques, and compared each of them to conditions of Good Agricultural Practice (i.e., full mineral fertilization and liming). Our results from main German agricultural LTEs show that an annual SOC accrual of several per mille is theoretically feasible at the field scale. We identified organic amendments as the key management strategy strongest in promoting SOC accrual at a given site, and liming as a management option had the highest risk of negative effects on SOC accrual. Sandy sites, with overall low SOC stocks, have the highest potential to accumulate SOC under optimized management practices and the highest potential to lose SOC under inappropriate farming options. In terms of absolute values, the highest SOC gain occurred at a sandy site (195 kg ha^{-1} yr^{-1}) with irrigation and straw application. The highest SOC loss occurred at a loamy site (-125 kg ha^{-1} yr^{-1}) by omission of N fertilization. Moreover, our analyses show that combination of specific management strategies can often attenuate negative impacts in terms of SOC accrual or amplify the positive effects. Our evaluation showed that soil type and time, rather than the specific type of management, is important for SOC gains. This is likely to be irrespective of the specific mechanisms that affect the balance between SOC input and decomposition, and should therefore hold true also for sites outside Germany.

Any gain in SOC at a given site by organic amendments may cause depletion or lack of accrual at other sites. Due to such C leakage, overall SOC sequestration is lower at the regional scale than indicated for site-specific management. Additionally, at the system scale, C losses during manure storage or CO_2 emission by material transport have to be considered; these were not accounted for in the present study. Nevertheless, the reported gains in SOC can be substantial. Variations in SOC stocks between sites can be substantial, which challenges the development of site-specific incentives for SOC accumulation.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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