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Effects of Agricultural Management on Water Retention via Changes in Organic Carbon in Topsoil and Subsoil

Laura E. Skadell[1] | Ullrich Dettmann[1] | Georg Guggenberger[2] | Axel Don[1]

[1]Thünen-Institute of Climate-Smart Agriculture, Braunschweig, Germany | [2]Institute of Earth System Sciences, Section Soil Sciences, Leibniz University Hannover, Hannover, Germany

Correspondence: Axel Don (axel.don@thuenen.de)

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ABSTRACT

Background: Increases in soil organic carbon (SOC) through agricultural management can alter soil water retention. This is determined via changes in pore size distribution, namely, air capacity (AC), plant-available water capacity (PAWC), and hygroscopic water capacity (HWC). However, it is uncertain how much soil water retention in topsoil and subsoil can be increased with agricultural management practices.

Aims: The aim of this study was to quantify the influence of different agricultural management practices commonly used in Central Europe on AC, PAWC, and HWC in topsoil and subsoil as a result of SOC changes in different soil types.

Methods: We sampled topsoil and subsoil at 11 sites across Germany that showed a management-induced SOC increase and a wide range of soil texture and measured the volumetric water content at different pressure heads from saturation to permanent wilting point.

Results: In topsoil, AC increased on average by 1.3 mm 100 mm^{-1} (+17%), PAWC by 1.6 mm 100 mm^{-1} (+8%), and HWC by 1.6 mm 100 mm^{-1} (+15%) per 10 g kg^{-1} increase in SOC. In subsoil, SOC was increased by incorporating compost or topsoil material, which increased AC by 10.0 mm 100 mm^{-1} (+134%), PAWC by 0.7 mm 100 mm^{-1} (+3%), and HWC by 0.5 mm 100 mm^{-1} (+7%) per 10 g kg^{-1} increase in SOC. The total average increase in PAWC was 1 mm in topsoil and 1 mm in subsoil, with SOC increases by 4 and 5 g kg^{-1}, respectively.

Conclusions: More than 50 years of additional farmyard manure addition resulted in an average SOC increase of 3.4 g kg^{-1}, but PAWC increased only slightly by 2.5%, showing the limited impact of agricultural management on water retention capacities.

1 | Introduction

Global climate change is threatening agricultural productivity. Rising temperatures are leading to more frequent and longer lasting periods of drought, which has a significant impact on plant productivity and therefore on yields. As a result, changing climatic conditions are affecting soil requirements, such as the provision of food, feed, and fiber, with water retention becoming a key issue (Feifel et al. 2024; Schindler et al. 2007).

The water retention capacity of soils is, however, highly dependent on soil texture and cannot be easily changed (Zhuang et al. 2001). One possible way to increase the water retention capacity is to enhance the soil organic carbon (SOC) content (Hudson 1994; Rawls et al. 2004). Higher SOC contents are likely to improve soil structure by promoting the formation of soil aggregates, which may decrease bulk density and increase total porosity (TP). These changes can create more space for soil water, potentially enhancing water infiltration and increasing plant-available water (Eden et al. 2017).

The "4 per mille Soils for Food Security and Climate" initiative, started at the COP21 climate summit in 2015, introduced a theoretical calculation according to which an increase of global SOC stocks by 4‰ is sufficient to offset all anthropogenic greenhouse gas emissions (Rumpel et al. 2020). With climate-smart agriculture, the initiative aims not only to mitigate climate change but also to adapt soils to more extreme climate conditions (Minasny et al. 2017). In this context, it is expected that an increase of SOC can significantly improve the plant-available water capacity (PAWC) of the soil by changes in pore size distribution, thus contributing to climate change adaptation (Ramírez et al. 2023).

Within a volume of soil, there are different pore size classes: large macropores (>50 µm), small macropores (50 to >10 µm), mesopores (10 to >0.2 µm), and micropores (≤0.2 µm). A larger volume of soil water in the macropores can move freely, whereas the soil water in the mesopores and micropores is stronger influenced by adhesion and cohesion forces. These occurs between water molecules and the soil matrix as well as between the water molecules themselves. There are parameters which describe specific ranges of the pore size distribution of a soil, namely, air capacity (AC; pore size: >50 µm), PAWC (pore size: 50 to >0.2 µm), and hygroscopic water capacity (HWC; pore size: ≤0.2 µm). The AC reflects how well water drains from the macropores after saturation, as well as its capability to supply plant roots with oxygen, hence describing the pore space that cannot hold water. The PAWC describes the amount of water between field capacity (FC) at a pressure head (for unsaturated conditions of $10^{1.8}$ cm (pF 1.8 = $10^{1.8}$/10 kPa; matric potential of −6.3 kPa) and permanent wilting point (PWP) at a pressure head of $10^{4.2}$ cm (pF 4.2 = $10^{4.2}$/10 kPa; matric potential of −1500 kPa). At pressure heads beyond PWP, water is only retained in micropores of the soil matrix, from which plants cannot extract it. This fraction of water is described as HWC, which is retained in soil by strong forces in the micropore system (AG Boden 2024; Román Dobarco et al. 2019).

In soil science, the influence of enhanced SOC content on the water retention capacities of a soil has been a long-lasting discussion (Bagnall et al. 2022; Huntington 2020; Minasny and McBratney 2018; Rawls et al. 2004; Weber et al. 2023 for a review). The majority of the studies show a positive correlation between SOC and the aforementioned capacities (e.g., Hudson 1994; Eden et al. 2017; Kay et al. 1997). Hudson (1994), for example, reported SOC effects on PAWC of 1.28 mm 100 mm^{-1} for sands and 2.51 mm 100 mm^{-1} for silt loam. Other studies reported rather limited effects, such as a meta-analysis by Minasny and McBratney (2018), with increases in TP, FC, PWP, and PAWC by 2.95 mm 100 mm^{-1}, 1.61 mm 100 mm^{-1}, 0.17 mm 100 mm^{-1}, and 1.16 mm 100 mm^{-1}, respectively, for every +10 g kg^{-1} SOC.

Regardless of the divergent effects, most of these studies focused on topsoil while overlooking the subsoil (>30 cm depth). However, this is where 30%–50% of the nutrients and more than 60% of the plant-available water are stored (Kautz et al. 2013). Hence, it is essential to be aware of the subsoils' potential to support plant growth, especially in time periods in which the topsoil has dried out. Model results from Minasny and McBratney (2018) stated that the SOC effect on water retention was even higher in subsoil. However, as both FC and PWP increased more distinctive, PAWC was still lower compared to PAWC in the topsoil. Feifel et al. (2024) also showed that an increase in SOC benefits soil water retention, but not in the upper 10 cm, where higher water retention led to increased evaporation and thus to a reduction in plant-available water. Therefore, the authors suggest incorporating organic matter at greater depths, which could help mitigate this effect. Moreover, results from Turek et al. (2023) are pointing to the depth-dependent incorporation of organic matter. They found that an increase by 2% SOC down to 65 cm reduced drought-induced transpiration in maize by almost 40 mm.

Given the limited number of subsoil studies that have not directly investigated the relationship between water retention and changes in SOC content, it is critical to fill this knowledge gap and investigate how SOC affects water retention, particularly at greater soil depths, in order to increase soil resilience to drought. We therefore sampled 11 sites in Germany that are managed by common farming practices to find out how AC, PAWC, and HWC changes with increasing SOC content in topsoil (0–30 cm) and subsoil (30–60 cm). The study included soil samples from four long-term experiments (56–68 years), where farmyard manure (FYM) was incorporated into the topsoil; four short-term experiments (1–5 years), where green waste compost was incorporated in either topsoil or subsoil; and three sites where the soil had been deep-ploughed (DP) once 51–54 years prior to sampling. Subsoil samples were collected from two of the four short-term experiments and from the DP sites (n = 5). Over all sites, the sampled soils showed a management-induced SOC gradient (0.7–16.1 g kg^{-1} on average) and a wide range of clay contents (3%–38%).

Using samples from both topsoil and subsoil, we aim to provide insights into the potential benefits of managing (subsoil) organic carbon for improved agricultural resilience by answering the following questions:

1. How do changes in organic carbon influence AC, PAWC, and HWC in topsoil and subsoil?
2. What implications do the results have for agricultural management with regard to adaptation to climate change?

2 | Materials and Methods

2.1 | Site Description and Soil Sampling

Samples for this study originated from 11 field experiments (sites) located in Germany (Table 1). All selected experiments had a management-induced SOC gradient and were sampled in the topsoil (0–30 cm), and five experiments (ST-CF1, ST-CF3, DP-BAN, DP-ELZ, and DP-ESM) were additionally sampled in

TABLE 1 | Meta data about the sampled experiments.

Name of the experiment used in this study	Official name and location of the experiment	Latitude	Longitude	MAT (°C)	MAP (mm year^{-1})	Soil type (according to KA6)	Average clay content (%)	Treatment of the sampled plots	Start year	Time of Sampling	Subsoil sampled	Associated literature/ Meta data
Group LT: Long-term experiments with farmyard manure addition												
LT-BAD	L28—Bad Salzungen	50.80	10.22	8.1	568	Su3, medium silty sand	7	30 Mg ha^{-1} FYM every 3 years	1966	April 2022	No	https://tools.bonares.de/ltfe/lte-details/332/ (last accessed: Oct. 28, 2024)
LT-EVG	Nutrient Depletion Experiment—Gießen	50.60	8.65	9.0	650	Lu, silty loam	22	30–40 Mg ha^{-1} year^{-1} FYM N: 180 kg ha^{-1} year^{-1}; P_2O_5: 45 kg ha^{-1} year^{-1}; K_2O: 60 kg ha^{-1} year^{-1}	1954	April 2022	No	Macholdt et al. (2019), Skadell et al. (2023)

Abbreviations: FYM, farmyard manure; MAP, mean annual precipitation; MAT, mean annual temperature.

the subsoil (30–60 cm). We assigned the sites to three groups depending on the duration and type of organic amendments: (1) long-term experiments of 56–68 years duration and FYM as organic amendment: LT-BAD, LT-EVG, LT-MET, and LT-SPR, (2) short-term experiments of 1 and 5 years duration and green waste compost as organic amendment: ST-ST-CF1, ST-CF3, ST-HOE, and ST-ROT, and (3) soils that were DP once 51–54 years before sampling with material from former topsoil incorporated into the subsoil: DP-BAN, DP-ELZ, and DP-ESM. All experiments were regularly ploughed down to 30 cm except for sites ST-HOE and ST-ROT, which were tilled to 20 and 15 cm, respectively. The treatment plots received either FYM only or FYM together with mineral nitrogen (N), phosphorus (P), and potassium (K) (Table 1). The reference plots received either no fertilizer or only NPK. The treatment plots at ST-CF1 and ST-CF3 were deep-loosened in stripes, and green waste compost was incorporated to a depth of 60 cm using a deep-slotting method (for further details, see Figure 1 and Schmittmann et al. 2021). The reference plots were only deep-loosened and received no organic amendments. In the DP soils, the topsoil is a mixture of topsoil and subsoil material due to the deep-ploughing treatment. The reference samples were taken from soil profiles regularly ploughed to a depth of 30 cm in the vicinity of the DP soils (Figure 1).

At each site, two undisturbed samples per field replicate (three to four) were taken by carefully inserting steel cylinders with a sharpened bottom edge and a volume of 244.29 cm^3 (height: 6 cm, diameter: 7.2 cm) vertically into the soil and excavating the whole sample. After collection, the samples were sealed with PVC caps and stored at 8°C. Ten samples were excluded due to disturbance by high stone content or large earthworms in the sample, which resulted in a sample set of 211 cylinders. Additionally, one disturbed sample was collected at each plot (n = 70) and stored in plastic bags at 8°C for permanent wiling point analysis.

2.2 | Determination of Water Retention Capacities

Water retention capacities—namely, the AC, PAWC, and HWC—were determined from parameterized soil water retention characteristics. These were derived from evaporation experiments for pressure heads ranging from 0 to approximately −800 cm and a dew-point potentiometer for water contents near the PWP at pF 4.2 (pF = log10(-pressure head)).

2.2.1 | Evaporation Experiments and Determination of Soil Bulk Density and TP

For sample preparation, the bottom of each steel cylinder was covered with gauze, and the samples were slowly saturated with water from the bottom for at least 2 weeks. To prevent evaporation from the top, the samples were loosely covered with a cap while maintaining atmospheric pressure connection.

Once saturated, the samples were weighted and placed on a mesh for at least 24 h to establish a pressure head of zero at the core bottom. Subsequently, water retention characteristics were determined using evaporation experiments (ku-pF apparatus, UGT GmbH, Müncheberg, Germany) (Dettmann et al. 2019).

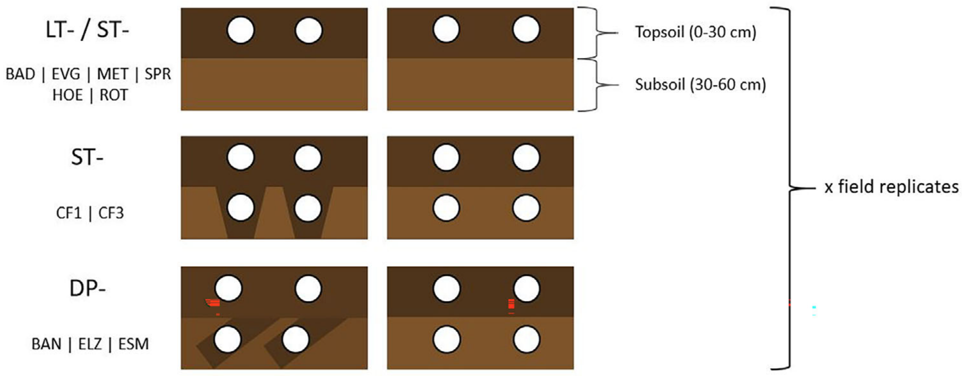

FIGURE 1 | Sampling design of the 11 field experiments. DP, deep-ploughed soils; LT, long-term experiments; ST, short-term experiments.

Two tensiometers were inserted horizontally at depths of 1.5 and 4.5 cm into the cores. The samples were kept under atmospheric conditions, with weight loss and tensiometer values recorded every 10 min. The experiments were terminated when the measurement range of the tensiometers (pressure heads >−800 cm) was reached.

After the experiment, samples were dried at 105°C until a constant weight was reached. Bulk density and porosity were determined with standard mass calculations based on the sample weight at the beginning and end of the experiment, the dry sample mass and volume of the fine soil, respectively. We assumed full saturation was achieved before the experiment and that the entire porosity was interconnected (Dettmann et al. 2019).

2.2.2 | Dew-Point Potentiometer

Pressure heads in the range of the PWP were measured using the WP4C dew-point potentiometer (Decagon Devices, Inc., Pullman, WA) on disturbed samples. The field moist samples were dried at air temperature and repeatedly measured during progressive drying. Before and after each measurement, samples were weighted. Once the samples reached water contents at pressure heads below pF 4.2, they were dried at 105°C, and gravimetrical water contents were calculated using standard mass calculations for each respective WP4C measurement. Volumetric water contents were then calculated by multiplying the gravimetrical water contents with the bulk density of the fine soil.

2.2.3 | Parameterization of Water Retention Characteristics

The water retention characteristics from the evaporation experiments were determined using the simplified evaporation method (Peters and Durner 2008; Schindler 1980), following Dettmann et al. (2019), with the R package *SoilHyP* (Dettmann 2023). All data points were interpolated using piecewise linear splines to ensure equal representation across the range of 0 to approximately −800 cm. Subsequently, a soil hydraulic function was fitted for each field replicate using data from the two replicated steel cylinders in the evaporation experiments and the dew-point potentiometer. The PDI model was used to present the soil hydraulic function (Peters et al. 2024).

2.2.4 | Determination of AC, PAWC, and HWC

Water retention capacities were calculated with the volumetric water contents derived from the parameterized soil hydraulic functions at the respective pressure heads. AC was calculated as the difference between the TP (saturated volumetric water content) and the water content at FC (corresponding to a pF of 1.8, or a pressure head of $10^{1.8}$ cm), PAWC was determined by subtracting the water content at FC from the water content at PWP (corresponding to a pF of 4.2, or a pressure head of $10^{4.2}$ cm), and HWC was defined as the water content at PWP.

The derived water retention capacities were converted from volumetric water content (cm^3 cm^{-3}) to water volume within a 100 mm deep soil column (mm 100 mm^{-1}) with:

$$x\ \left(\mathrm{cm}^3\ \mathrm{cm}^{-3}\right) = x \times 100\ \mathrm{Vol\%} = x \times 100\ \left(\mathrm{mm}\ 100\ \mathrm{mm}^{-1}\right). \quad (1)$$

2.3 | SOC Content and Soil Texture

Each undisturbed soil sample was dried at 105°C and sieved to <2 mm to determine the carbon and nitrogen content, which was done via dry combustion with an elemental analyzer (LECO, TruMac, St. Joseph, MI, USA). The soil texture was determined by feel following Vos et al. (2016).

2.4 | Comparison of Water Retention Capacities Obtained by Measurement or Pedotransfer Function (PTF)

We compare our results with a PTF in order to explore their ability to predict soil physical properties and may substitute direct measurements. This was carried out with the PTF after Wösten et al. (1999), which estimated the van Genuchten parameters θ_s (cm^3 cm^{-3}) (saturated water content), α (cm^{-1}) (approximately the inverse of the air-entry value), n (–) and m (–) (empirical shape-defining parameters) with regard to texture, SOC, bulk density of the fine soil, and soil depth.

The calculated van Genuchten parameters were then used in the soil hydraulic function to calculate the water retention capacities as described in Sections 2.2.3 and 2.2.4.

2.5 | Statistical Analysis and Other Calculations

To investigate the relationship between the predictor variable SOC content and the response variables (1) TP, (2) AC, (3) PAWC, and (4) HWC in topsoil and subsoil, obtained from measurement data and from the PTF described under Section 2.4, we used linear mixed-effects models fitted by restricted maximum likelihood (REML). The models were specified as

(I)–(IV) $\text{model}_{\text{topsoil}}$: response $\text{variable}_{(\text{i}),(\text{ii}),(\text{iii}),(\text{iv})} \sim \text{SOC} + (\text{SOC}|\text{site})$, and

(V)–(VIII) $\text{model}_{\text{subsoil}}$: response $\text{variable}_{(\text{i}),(\text{ii}),(\text{iii}),(\text{iv})} \sim \text{SOC} + (\text{SOC}|\text{site})$,

with SOC as fixed and site as random factor.

The random effects structure allowed the intercept and the effect of the predictor variable (slope) to vary by site, thereby accounting for site-specific variability in the relationship between the predictor variable and the respective response variables. All models were fitted using the *lmer* function from the *lme4* package in R (Bates et al. 2015). To assess the significance of fixed effects, we used Satterthwaite's method for calculating degrees of freedom and t values, as implemented in the *lmerTest* package (Kuznetsova et al. 2017).

The models (I)–(VIII) were also fitted with the response variables (i)–(iv) calculated from the van Genuchten parameters of the PTF (Section 2.4). For the purpose of determining the extent to which the results of the linear mixed-effects model of the measured data and the results of the PTF agree or disagree, we compared the respective mean capacities and slopes. We defined that the results of the mean capacities to be of the same order of magnitude if their ratio (r_m) is $0.2 \le r_m \le 1.2$ and the slopes to be of the same order of magnitude if their ratio (r_s) is $0.5 \le r_s \le 1.5$.

Significance was set at a level of $\alpha = 0.05$. SOC effect, corresponding to the slope of the respective regression, was defined as follows:

$$\text{SOC effect} = \frac{\Delta y}{\Delta x} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{\Delta \text{ response variable}}{\Delta \text{ soil organic carbon}}, \tag{2}$$

with the site- and depth-specific SOC effects, the actual increase (absolute and relative) in PAWC (per 100 mm of soil) was calculated as follows:

$$\text{PAWC}_{\text{Reference}} = \text{SOC effect}_{\text{Site | Depth}} \times \text{SOC content}_{\text{Reference}} + \text{intercept}, \tag{3}$$

$$\text{PAWC}_{\text{Treatment}} = \text{SOC effect}_{\text{Site | Depth}} \times \text{SOC content}_{\text{Treatment}} + \text{intercept}, \tag{4}$$

$$\Delta \text{ PAWC}_{\text{Absolute}} = \text{PAWC}_{\text{Treatment}} - \text{PAWC}_{\text{Reference}}, \tag{5}$$

$$\Delta \text{ PAWC}_{\text{Relative}} = \frac{\Delta\text{PAWC}_{\text{Absolute}}}{\text{PAWC}_{\text{Reference}}} \times 100\%. \tag{6}$$

To see how much the increase in the topsoil (per 300 mm of soil) and subsoil (per 300 mm of soil) was, the $\Delta\text{PAWC}_{\text{Absolute}}$ value was multiplied by three.

All statistical analyses were conducted using R (version 4.4.0).

3 | Results

3.1 | The Relationship Among SOC, Bulk Density, and TP

The range in topsoil carbon content due to the different agricultural management at the 11 experiments was between 5 and 49 g kg^{-1} with an average of 13 g kg^{-1}. The difference in SOC due to the agricultural management between treatment and reference was for the experiments in group LT on average 3.4 g kg^{-1} (+39%), for group ST 5.4 g kg^{-1} (+36%) and for the DP soils of group DP −3.4 g kg^{-1} (−23%) (Supporting Information S2). In subsoil, SOC content ranged from 1 to 21 g kg^{-1} with an average of 7 g kg^{-1}. Here, the incorporation of compost (group ST) increased SOC on average by 3.1 g kg^{-1} (+70%) and deep-ploughing (group DP) increased subsoil SOC by on average 6.8 g kg^{-1} (+180%). The bulk density in topsoil was on average 1.4 g cm^{-3} with a minimum value of 1.0 g cm^{-3} and a maximum value of 1.7 g cm^{-3}. Agricultural management decreased topsoil bulk density by 0.09 g cm^{-3} (−6%) in group LT, by 0.05 g cm^{-3} (−4%) in group ST and increased topsoil bulk density by 0.09 g cm^{-3} (+7%) in group DP. In subsoil, the bulk density was on average 1.5 g cm^{-3}, ranging from 0.8 to 1.7 g cm^{-3}. Agricultural management decreased subsoil bulk density by 0.3 g cm^{-3} (−19%) in group ST and by 0.03 g cm^{-3} (−2%) in group DP. With increasing SOC content, bulk density decreased at every site ($R^2 = 0.5$) except at ST-HOE in topsoil and at DP-BAN and DP-ELZ in subsoil. Across all sites, bulk density decreased by 0.3 g cm^{-3} for every +10 g kg^{-1} increase in SOC, with highest changes at ST-CF3 in subsoil (−1.2 g cm^{-3}) and lowest negative changes at DP-ESM in subsoil with 0.1 g cm^{-3} (Figure 2). TP was positively correlated with the SOC content, with on average +5.2 mm 100 mm^{-1} per 10 g kg^{-1} increase in SOC (Supporting Information S2). Exceptions were found at ST-HOE in topsoil and DP-BAN in subsoil, where higher SOC contents resulted in a lower TP. In subsoil, TP increased on average by 10.3 mm 100 mm^{-1} for every +10 g kg^{-1} SOC (Figure 2).

3.2 | Influence of Organic Carbon on Water Retention Capacities in Topsoil and Subsoil

The effect of enhanced SOC on the soil's pore capacities measured as AC, PAWC, and HWC was in a similar range among the three parameters in the topsoil but largely divergent and inconsistent in the subsoil (Table 2). Across all experiments, AC increased on average by 1.3 mm 100 mm^{-1} (+17%), PAWC by 1.6 mm 100 mm^{-1} (+8%), and HWC by 1.6 mm 100 mm^{-1} (+15%) (Supporting Information S2). In subsoil, AC increased by 10.0 mm 100 mm^{-1} (+134%), PAWC by 0.7 mm 100 mm^{-1} (+3%), and HWC by 0.5 mm 100 mm^{-1} (+7%).

Regarding the three different experimental groups (Table 1), SOC effects on AC and PAWC were similar in the topsoil. Long-term FYM addition (group LT) increased AC by 1.1 mm 100 mm^{-1},

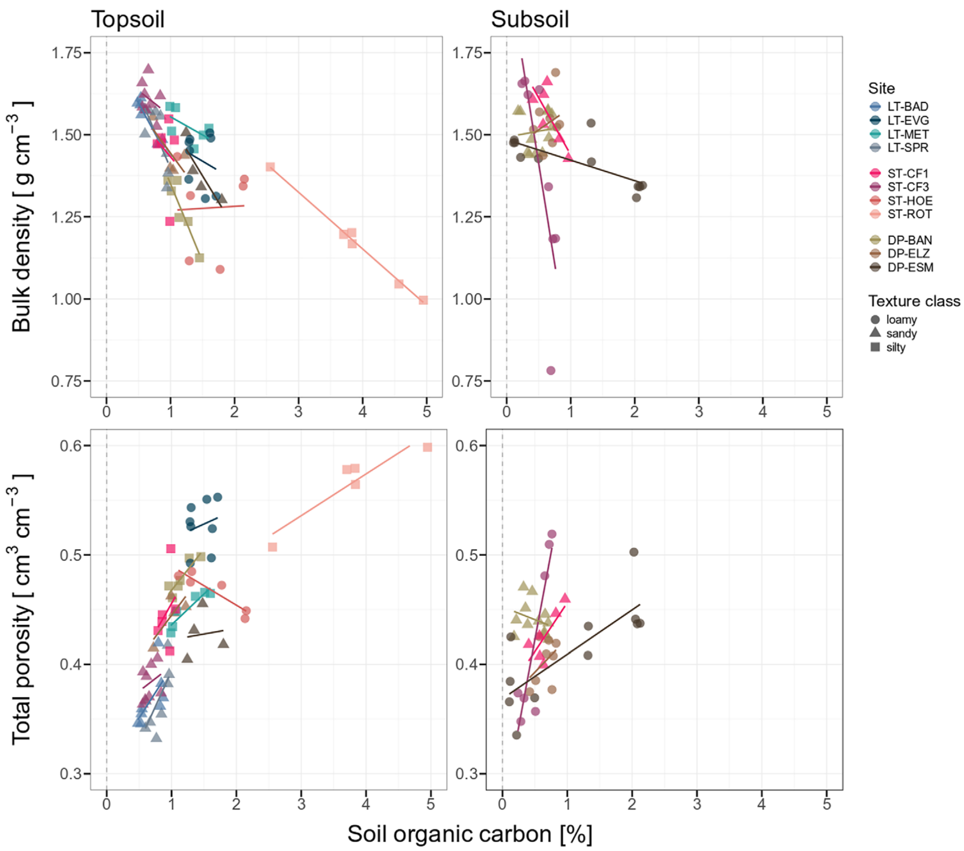

FIGURE 2 | Relationship between soil organic carbon content and bulk density and total porosity in topsoil and subsoil across the 11 field experiments.

short-term compost addition (group ST) led to a higher AC of 1.3 mm 100 mm^{-1}, and the DP soils (group DP) showed a higher AC of 1.7 mm 100 mm^{-1} for every +10 g kg^{-1} SOC (Table 2). Long-term FYM application increased topsoil PAWC by 1.8 mm 100 mm^{-1}, short-term compost addition increased PAWC by 1.3 mm 100 mm^{-1}, and deep-ploughing increased PAWC by 1.9 mm 100 mm^{-1} for every +10 g kg^{-1} SOC. Moreover, HWC in topsoil increased with SOC in all three groups of experiments but with different magnitude: Long-term FYM application increased HWC by 1.5 mm 100 mm^{-1}, whereas short-term compost addition increased HWC by 0.9 mm 100 mm^{-1}, and deep-ploughing increased HWC the most with +2.7 mm 100 mm^{-1} for every +10 g kg^{-1} SOC.

The effects in the subsoil were less consistent. The AC of the short-term experiments increased on average by 23.2 mm 100 mm^{-1} and much less in the DP soils (1.2 mm 100 mm^{-1}). Changes in PAWC showed inconsistent SOC effects in the subsoil with a decrease by 4.2 mm 100 mm^{-1} in the short-term experiments and an increase by 3.9 mm 100 mm^{-1} due to deep-ploughing. Moreover, HWC in subsoil was differently affected by SOC in the groups with positive effects in the short-term experiments (3.1 mm 100 mm^{-1}) and negative effects in the DP soils (−1.3 mm 100 mm^{-1}).

With the site-specific regression equation obtained from the linear mixed-effects model (see Equations 3–6; Supporting Information S2), an absolute and relative increases of PAWC per 100 mm and 300 mm were calculated on the basis of the actual SOC increase at a certain site and depth (see Section 3.1; Table 3). For the LT group, PAWC increased by 0.5 mm 100 mm^{-1}, which is a relative increase of 2.5%. Within the upper 30 cm, PAWC increased by 1.6 mm due to FYM addition over 56–68 years at the four long-term experiments.

On average, short-term management with incorporation of green waste compost (group ST) increased PAWC less compared to the long-term experiments, namely, by 0.2 mm 100 mm^{-1}, which is a relative increase of 0.6%. At ST-HOE and ST-ROT, the SOC content was strongly increased by the treatment, but in contrast to ST-ROT, ST-HOE showed negative effects on PAWC (−13%), which strongly contributed to the less positive result. In the complete topsoil, PAWC increased by 0.6 mm.

Deep-ploughing lowered the PAWC due to the dilution with subsoil material by 0.4 mm 100 mm^{-1}. This is equivalent to a relative decrease in PAWC by 1.0 mm and a total PAWC decrease of 1.2 mm in the topsoil.

In the subsoil, short-term management with compost addition resulted in inconsistent changes in PAWC, with a decrease by 3.8 mm 100 mm^{-1} (−18.9%) at one site (sandy site ST-CF3) and an increase in PAWC by 0.5 (+2.3%) and the other site (loamy site ST-CF1).

In the subsoil of the DP soils (group DP), PAWC increased due to the incorporation of organic-rich topsoil material by 2.6 mm 100 mm^{-1}. This is equivalent to a relative increase in PAWC by

TABLE 2 | Mean soil organic carbon (SOC) effects ± standard deviation (SD) on soil physical properties in mm 100 mm^{-1} per experimental group.

Response variable	Depth	Group	SOC effect ± SD (mm 100 mm^{-1})
TP	Topsoil	Long-term	7.1 ± 3.2
TP	Topsoil	Short-term	3.7 ± 4.1
TP	Topsoil	Deep-ploughed	4.9 ± 1.1
AC	Topsoil	Long-term	1.1 ± 0.3
AC	Topsoil	Short-term	1.3 ± 0.6
AC	Topsoil	Deep-ploughed	1.7 ± 0.6
PAWC	Topsoil	Long-term	1.8 ± 1.2
PAWC	Topsoil	Short-term	1.3 ± 2.9
PAWC	Topsoil	Deep-ploughed	1.9 ± 3.8
HWC	Topsoil	Long-term	1.5 ± 1.2
HWC	Topsoil	Short-term	0.9 ± 1.7
HWC	Topsoil	Deep-ploughed	2.7 ± 0.1
TP	Subsoil	Short-term	22.2 ± 19.0
TP	Subsoil	Deep-ploughed	2.3 ± 2.7
AC	Subsoil	Short-term	23.2 ± 28.8
AC	Subsoil	Deep-ploughed	1.2 ± 3.4
PAWC	Subsoil	Short-term	−4.2 ± 8.9
PAWC	Subsoil	Deep-ploughed	3.9 ± 5.1
HWC	Subsoil	Short-term	3.1 ± 3.2
HWC	Subsoil	Deep-ploughed	−1.3 ± 7.2

Abbreviations: AC, air capacity; HWC, hygroscopic water capacity; PAWC, plant-available water capacity; TP, total porosity.

13.1% and an increase by 5.9 mm (assuming that 74% is buried topsoil) in the total subsoil from 30 to 60 cm depth (Figure 3).

3.3 | Comparison of Water Retention Capacities Obtained by Measurements or PTF

To see to what extent the soil water retention measurements and their prediction by a PTF agree, we extracted the mean capacities as well as the mean SOC effects per site and depth from the linear mixed-effects model results for measured data and PTF data, as described in Section 2.5. The mean capacities were highest for PAWC in topsoil (91%) and lowest for HWC in subsoil (9%) (Table 4, Figures 4 and 5). The mean capacities for AC and HWC were consistent between topsoil and subsoil, but PAWC showed better agreement with the PTF in topsoil compared to subsoil. The SOC slopes were highest for HWC in subsoil (40%) and lowest for HWC in topsoil (9%). Although the SOC effect was similar in both depth increments for AC and PAWC, the agreement with the PTF was better for HWC in subsoil (40%) than in topsoil (9%). With regard to the duration of the experiments, a longer duration (LT and DP groups together) led to a higher agreement between the measured and predicted values, except for AC in the topsoil and HWC in the topsoil (Table 4).

In the subsoil, the AC and PAWC of ST-CF3 showed low agreement. The SOC effect of AC predicted with the PTF was negative and not as steep as for the directly measured values (Figure 5; Figure S2). Moreover, the mean capacity value of AC was higher for the measured data compared to the results from the PTF. At DP-BAN, the subsoil PAWC differed strongly from the predicted value by the PTF. The latter showed a negative effect of SOC on PAWC, whereas the measurements came to the opposite result.

3.4 | Effects of SOC on Water Retention Capacities in Relation to Soil Texture

The sample set covered a wide range of clay contents, ranging from 3% to 38% in topsoil and from 3% to 17% in subsoil, with an average clay content of 12% in topsoil and 8% in subsoil (Figure S1).

The SOC effects on the target variables TP, AC, and HWC were slightly stronger in soils with higher sand content (Figure 5). In contrast, no such texture influence was found for PAWC. In subsoil, SOC effects on PAWC are higher in clayey than in sandy soils. However, SOC effects became stronger in both topsoil and subsoil the higher the silt content was (Figure S3). This was especially visible at DP-BAN, ST-ROT, and ST-CF1, where PAWC increased by 5.6 mm 100 mm^{-1}, 3.4 mm 100 mm^{-1}, and 3.2 mm 100 mm^{-1} per +10 g kg^{-1} SOC (Figure 6).

4 | Discussion

4.1 | How Do Changes in Organic Carbon Influence AC, PAWC, and HWC in Topsoil and Subsoil?

Water retention in the soil is driven by adsorption or capillary forces. Capillary water is held in soil pores, whereas adsorbed water is tightly bound as thin film around soil particles (Zhou et al. 2020). Changes in SOC content affected the water retention capacities of the soils via changes in pore size distribution. The input of organic matter to soil lowered the soil bulk density and enhanced its structure due to improved aggregate formation (Zhou et al. 2020). A mix of different pore sizes promotes drainage and aeration and can increase water availability for the plants (Naveed et al. 2014). With more SOC in the soil, as all pore size classes and thus also the TP increased, which consequently means that a larger number of pores is available for air and water storage (Eden et al. 2017).

We observed an increase in TP by 5.5 mm 100 mm^{-1} per increase of 10 g kg^{-1} SOC across all sites, which is less than half of the increase reported by Celik et al. (2004) after short-term compost and FYM application in a loamy soil with 37% clay on average. Their study found that TP increases in topsoil were more pronounced in the compost treatment, with a rise of 12.5 mm 100 mm^{-1}, although with much less compost (25 vs. 82 Mg ha^{-1} at ST-HOE and ST-ROT). However, the duration of their study was 5 years with annual compost incorporation, whereas the experimental duration of ST-HOE and ST-ROT at the time of sampling was only 9 months, and the compost was only incorporated once.

TABLE 3 | Average change of soil organic carbon content (ΔSOC; treatment minus reference) per site and depth, average absolute and relative change in plant-available water capacity (ΔPAWC, treatment minus reference) per site and depth, and absolute change of PAWC in 0–30 cm and 30–60 cm.

Site	Depth	ΔSOC ($g\ kg^{-1}$)	ΔPAWC ($mm\ 100\ mm^{-1}$)	ΔPAWC (%)	ΔPAWC ($mm\ 300\ mm^{-1}$)
LT-BAD	Topsoil	3.1	0.9	3.7	2.6
LT-EVG	Topsoil	3.3	0.4	2.3	1.3
LT-MET	Topsoil	4.7	0.1	0.5	0.4
LT-SPR	Topsoil	2.6	0.7	3.4	2.2
Mean		**3.4**	**0.5**	**2.5**	**1.6**
ST-CF1	Topsoil	1.7	0.5	2.5	1.6
ST-CF3	Topsoil	−0.7	−0.1	−0.5	−0.3
ST-HOE	Topsoil	10.5	−3.1	−12.9	−9.3
ST-ROT	Topsoil	10.0	3.4	13.5	10.2
Mean		**5.4**	**0.2**	**0.6**	**0.6**
DP-BAN	Topsoil	−2.6	−1.5	−4.3	−4.4
DP-ELZ	Topsoil	−3.0	−0.6	−2.7	−1.7
DP-ESM	Topsoil	−4.4	0.9	4.0	2.6
Mean		**−3.4**	**−0.4**	**−1.0**	**−1.2**
ST-CF1	Subsoil	2.5	0.5	2.3	1.6
ST-CF3	Subsoil	3.7	−3.8	−18.9	−11.5
Mean		**3.1**	**−1.6**	**−8.3**	**−4.9**
DP-BAN	Subsoil	3.3	3.2	10.7	7.0
DP-ELZ	Subsoil	1.1	−0.1	−0.4	−0.2
DP-ESM	Subsoil	16.1	4.8	28.9	10.7
Mean		**6.8**	**2.6**	**13.1**	**5.9**

TABLE 4 | Agreement of mean capacity values and soil organic carbon (SOC) effects of the variables air capacity (AC), plant-available water capacity (PAWC), and hygroscopic water capacity (HWC) in topsoil and subsoil between measurement data and data predicted by a pedotransfer function.

Variable	Depth	Agreement of mean capacity (%)	Agreement of mean capacity higher in long-term (LT) or short-term (ST) experiments?	Agreement of SOC effects (%)	Agreement of SOC effect higher in LT- or ST-experiments?
AC	Topsoil	55	LT	27	ST
AC	Subsoil	40	LT	20	LT
PAWC	Topsoil	91	LT	18	Equal
PAWC	Subsoil	60	LT	20	LT
HWC	Topsoil	18	Equal	9	LT
HWC	Subsoil	20	ST	40	LT

Abbreviations: LT, long-term experiments; ST, short-term experiments.

Therefore, the amount of compost may not have been sufficient and was not sufficiently homogenized in the soil to have its full effect on water retention. On the other hand, our findings align with the results from Naveed et al. (2014), particularly in long-term managed sites with application of FYM that resulted in an increase in TP of approximately 7 mm 100 mm^{-1}. This is a similar increase as we observed it in the long-term experiments with FYM application.

Very striking are the strong increases in the subsoil TP (and likewise in the subsoil AC) of the short-term experiments, where TP increased by 10.3 mm 100 mm^{-1}. These large increases

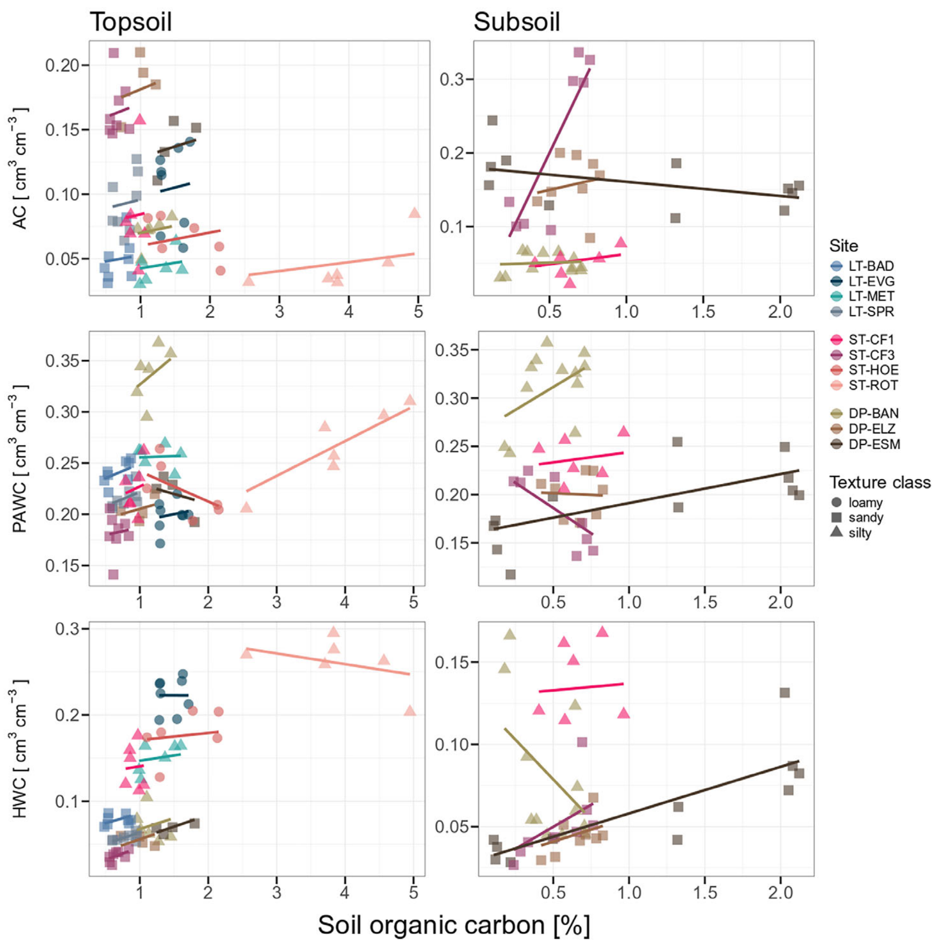

FIGURE 3 | Relationship between soil organic carbon and AC, PAWC, and HWC in topsoil and subsoil. AC, air capacity; HWC, hygroscopic water capacity; PAWC, plant-available water capacity.

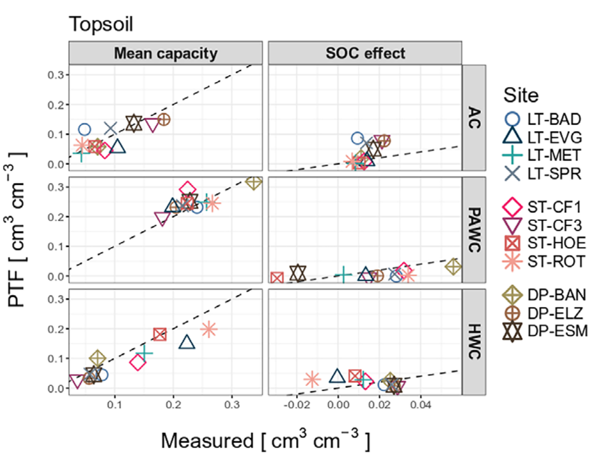

FIGURE 4 | Comparison of mean capacity values and SOC effects of AC, PAWC and HWC per site in topsoil (0–30 cm) obtained from either a PTF (*y*-axis) or from measurements (*x*-axis). AC, air capacity; HWC, hygroscopic water capacity; PAWC, plant-available water capacity; PTF, pedotransfer function; SOC, soil organic carbon.

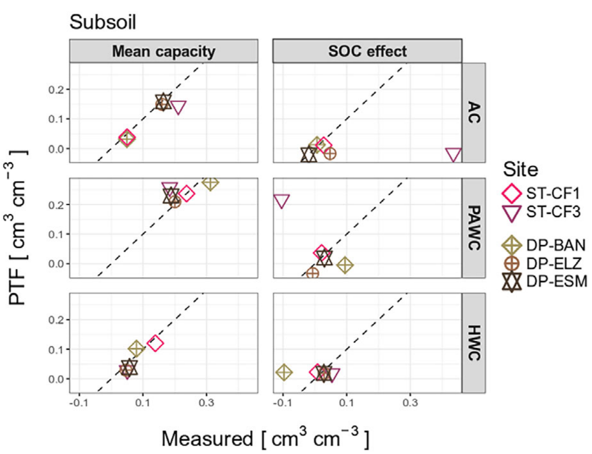

FIGURE 5 | Comparison of mean capacity values and SOC effects of AC, PAWC and HWC per site in subsoil (30–60 cm) obtained from either a PTF (*y*-axis) or from measurements (*x*-axis). AC, air capacity; HWC, hygroscopic water capacity; PAWC, plant-available water capacity; PTF, pedotransfer function; SOC, soil organic carbon.

are probably due to the additional deep-loosening effects that preceded the compost incorporation and not solely due to the increase in SOC. The loosening of the subsoil structure by deep tillage tends to quickly re-compact, which may have been prevented by the compost incorporation (Bauke et al. 2024). This strong increase in TP in subsoil, however, was only observed at ST-CF3, the sandy site, but not at ST-CF1, the loamy site, indicating texture-dependent effects, which are further discussed in Section 4.3.

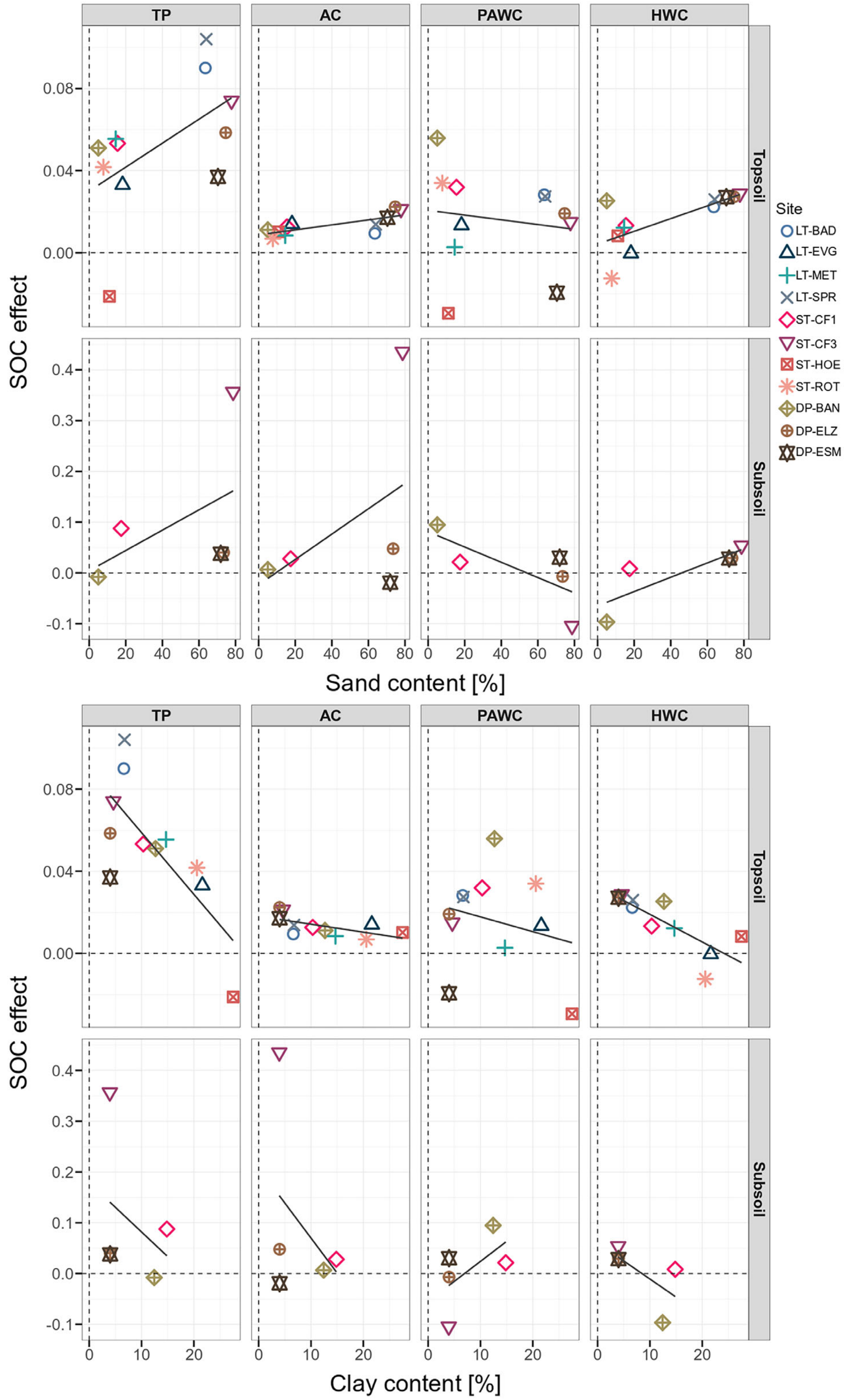

FIGURE 6 | Relationship of SOC effect and sand content (top) and clay content (bottom) in topsoil and subsoil at each site. AC, air capacity; HWC, hygroscopic water capacity; PAWC, plant-available water capacity; SOC, soil organic carbon; TP, total porosity.

The AC of a soil is an important measure of the soil aeration, structure, and drainage (Thomasson 1978). A high AC has the potential to reduce soil erosion by improved water infiltration and thus slow down surface run-off. Erosion is of increased concern in many agricultural regions due to climate change and the occurrence of extreme weather events such as extreme rainfall (Haghnazari et al. 2015). Moreover, soils with low air-filled pore space (<10%) are prone to waterlogging and anoxic conditions, which in turn hampers root growth (Bengough et al. 2011). With an average increase by 1.3 mm 100 mm^{-1} in topsoil, AC was 17% higher, which is moderate and in line with Minasny and McBratney (2018), who reported similar increases (1.34 mm

100 mm^{-1}). Regarding the three different groups, SOC effects on topsoil AC were in a similar range (1.1 mm 100 mm^{-1} to 1.7 mm 100 mm^{-1}), which allows the conclusion that neither the type of organic matter nor the experimental duration was of importance regarding the creation of macropores in the soil, which basically form the AC. In the subsoil, however, AC increased on average by 10.0 mm 100 mm^{-1} or 134%. The high increase in subsoil was caused by the short-term compost experiments together with soil disturbance due to deep-loosening.

The PAWC is a parameter that represents the range of water availability between two matric potentials: FC at −6.3 kPa and PWP at −1500 kPa. Within this range, water is considered available to plants for uptake but also hold against gravimetry. However, it is essential to note that the actual FC and PWP of a crop can deviate from these boundaries, depending on the transpiring plant and the root system (Bonfante et al. 2020). For many crops, FC typically ranges between −10 and −50 kPa, whereas PWP can span from −800 to −1500 kPa (Bonfante et al. 2020; Bouma 2018). We need to take this limitation into account, for example, by also discussing SOC effects on HWC and AC. The PAWC, as defined commonly, is used because of its practicability and standardization, which facilitates comparability across different soil types and across studies. It is still providing a sufficiently comprehensive overview of soil water conditions, whereas the additional complexity of a crop and soil type specific PAWC may not always be necessary or feasible for standard agricultural management.

We found that PAWC increased on average by 1.6 mm 100 mm^{-1} in topsoil and by 0.7 mm 100 mm^{-1} in subsoil for every 10 g kg^{-1} increase in SOC, which refers to an increase by 8% and 3%, respectively. This is in line with the results by a meta-analysis of Minasny and McBratney (2018), who concluded that effects of SOC on soil physical properties are rather limited. The authors included 60 studies and global data sets with more than 50,000 measurements into their analysis. The increase in PAWC was in the same range as in the present study, with 1.16 mm 100 mm^{-1} in topsoil and 0.81 mm 100 mm^{-1} in subsoil for every increase in SOC by 10 g kg^{-1}. Other studies have observed higher topsoil values, such as Kay et al. (1997) and Bagnall et al. (2022), who reported an increase by 2 mm 100 mm^{-1} and 3 mm 100 mm^{-1}, respectively, per +10 g kg^{-1} SOC increase across different soil textures. Yost and Hartemink (2019a) found an increase of PAWC by 5 mm 100 mm^{-1} per 10 g kg^{-1} SOC in a sandy soil. Eden et al. (2017) summarized the effect of organic amendments on PAWC from 17 studies with long-term experiments and concluded that PAWC generally increased with more SOC by 2.83 mm 100 mm^{-1}, with a 5 g kg^{-1} increase in SOC (FYM), and by 0.21 mm 100 mm^{-1}, with a 2.8 g kg^{-1} increase in SOC (compost). As stated in their review, a study by Leroy et al. (2008) reported even negative effects, but without providing a possible explanation. However, all of these studies, except the one from Minasny and McBratney (2018), refer to topsoils only and not to subsoil. In the subsoil of the present study, the PAWC was reduced at ST-CF3 (short-term compost experiment) due to an increase in SOC content. At this site, AC has been largely increased. However, an improvement in soil structure and thus an increase in AC can lead to a loss of PAWC, as aggregation can reduce the volume of intermediate pores (Jamison and Kroth 1958; MacRae and Mehuys 1985).

At the DP sites, the PAWC decreased in topsoil (−1.0%) and increased in subsoil (+13.1%; Table 3). This was due to deep-ploughing lowering the SOC content in the topsoil as a result of dilution with subsoil material (with a lower SOC content) and increased the SOC content in parts of the subsoil due to burial of SOC-rich topsoil material. The increases at DP-ESM in subsoil were even greater but also because of a high SOC increase. At DP-ELZ, however, effects on subsoil PAWC were in the opposite direction (−0.4%) compared to DP-BAN and DP-ESM but also with the lowest SOC increase (+1.1 g kg^{-1}). Burger et al. (2023) analyzed macroaggregate formation at the three sites and found it to be elevated only in the buried topsoil at DP-ESM, whereas it decreased at DP-BAN and was intermediate at DP-ELZ. On the basis of these results, particularly at DP-ESM, deep-ploughing appeared to enhance soil structure by increasing SOC content in the subsoil, which in turn promoted macroaggregate formation and improved PAWC (Burger et al. 2023). However, the results from DP-BAN were contradictory: although we observed indirect positive effects on subsoil structure through increased PAWC, Burger et al. (2023) reported signs of soil compaction due to the breakdown of macroaggregates into microaggregates. This is likely because silty soils, such as those at DP-BAN, are especially sensitive to disturbance by tillage under moist conditions (Schneider et al. 2017). Moreover, deep-ploughing as a management practice for SOC build-up in the subsoil is a specific and intensive strategy that is uncommon in many agricultural systems, so its effects may not be widely generalizable. Accordingly, our findings may have limited applicability in regions dominated by low- or no-till systems and should be interpreted in the context of conventional tillage in Central Europe.

An increase in SOC can increase the number of micropores (<0.2 µm) in which the water is bound so tightly that the roots cannot access it, thereby increasing the HWC. On one hand, with higher SOC, there are more functional groups in the soil that can adsorb water (e.g., carboxyl, phenolic hydroxyl, or amino groups). On the other hand, an increase in SOC can lead to the formation of organic-mineral complexes, resulting in a partial coverage of the surfaces of mineral particles and thus reducing the sorption sites for water molecules (Kaiser and Guggenberger 2003; Zhou et al. 2020). However, our results indicate that the first-mentioned processes dominate as HWC increased with increasing SOC content at almost all sites in topsoil and subsoil by 1.6 mm 100 mm^{-1} and 0.5 mm 100 mm^{-1}, respectively.

4.2 | Can PTFs Replace Laboratory Measurements?

PTFs can be used as alternatives to costly and time-consuming laboratory measurements to estimate soil properties such as PAWC (Rawls et al. 2004). However, their use can be problematic as the predictions are subject to uncertainties. Additional predictors such as land use or climate, which are often not considered by PTFs, could improve this (Weber et al. 2024).

On average, moderate to high agreement was identified for the mean capacities of AC, PAWC, and HWC in topsoil, with best agreement for PAWC in topsoil. The mean capacities in subsoil of AC and PAWC differed more from the PTF results than the mean capacities in topsoil, probably because the assessment of the subsoil is generally more complicated due to the lower SOC content and the greater variability of SOC (Hobley et al. 2018).

The results of the experiments with a longer duration (LT and DP) were better predicted by the PTF than the short-term experiments, with the exception of topsoil AC and topsoil HWC, where the prediction agreed equally. In the subsoil, the AC of ST-CF3 varied strongly, and likewise the bulk density, which was strongly reduced by 1.22 g cm^{-3} per increase of 10 g kg^{-1} SOC due to the deep-loosening right before the compost incorporation. As discussed above, this had a major impact on AC, which is characterized by the large pores (>50 μm). This change in AC was not solely related to the increase in SOC, but by the deep-loosening itself, and thus not predictable by the PTF. This also applies to the PAWC of the subsoil at the same site. Similarly, in the subsoil at DP-BAN, the PAWC predicted by the PTF showed a negative SOC effect, whereas the measurements came to the opposite result. However, the results from the PTF are consistent with the results of Burger et al. (2023).

We conclude that PTFs can be principally useful for determining the hydraulic properties of the soil. However, the study shows limitations when two changes occurred simultaneously in the subsoil: an increase in the SOC content and soil disturbance through physical disturbances (deep-ploughing and deep-loosening). These factors affected the water retention capacity of the soil in different ways, and the PTF only seems to be able to capture the effects of SOC. Thus, their accuracy is limited, as they do not consider physical disturbances. However, PTFs can be a valuable alternative to direct measurements in certain contexts, particularly where measurements are difficult, costly, or unavailable. Nonetheless, measurements remain crucial, especially for soils, management practices, and geographies where PTFs may not yet be well developed or applicable.

4.3 | Do the SOC Effects Vary Depending on Soil Texture?

The effects of SOC on TP and HWC was more pronounced in sandy soils as compared to clayey soils (Figure 5). However, PAWC increased the most in silty soils (Figure S2), which is supported by Hudson (1994), who found higher SOC effects on PAWC for silt loam (2.51 mm 100 mm^{-1}) and lower effects for sands (1.28 mm 100 mm^{-1}). Other studies reported stronger effects on PAWC in coarse textured soils (Minasny and McBratney 2018; Kay et al. 1997; Jamison and Kroth 1958; Rawls et al. 2004). An increase in SOC fosters the formation of soil aggregates and aggregate stability, thereby influencing pore structure and TP (Chenu et al. 2000; Zhou et al. 2020). To maintain the stability of the soil structure, which has consequences for soil water retention, more organic matter can be required as the clay content increases (Huntington 2020). In this context, the initial SOC content of a soil must also be taken into account, as the effects on water retention are more pronounced in soils with a low initial SOC content and decrease the higher the initial SOC content is. Sandy soils generally have a lower SOC content compared to clayey or loamy soils (Yost and Hartemink 2019b). Therefore, higher SOC effects in coarse-textured soils can also be caused by the initial SOC content and not by texture alone (Rawls et al. 2004). This was also the case in our study (disregarding two outliers at topsoil ST-ROT and subsoil ST-CF3), where effects of PAWC were significantly higher the lower the initial SOC content was (PAWC = −3.6 mm 100 mm^{-1} + 5.3 mm 100 mm^{-1}), however, with a moderate R^2 of 0.27.

4.4 | What Implications Do the Results Have for Agricultural Management With Regard to Adaptation to Climate Change?

The year 2024 was the warmest on record, with global average temperatures exceeding pre-industrial levels by 1.5°C for the first time. This resulted in 41 additional days of extreme heat added by climate change (Otto et al. 2024). As a result of increasing heat days, more water will be lost from soils and crops via evapotranspiration (Zhao et al. 2022). Arable land in areas where precipitation and water retention are already limited (e.g., sandy soils in arid or semi-arid climates) are particularly affected (Ladányi et al. 2021). Further, under these climatic conditions also water losses due to evapotranspiration are higher. As an example, the average potential evapotranspiration in Germany during July (2018) as peak of the vegetation season was 5.4 mm per day (Deutscher Wetterdienst 2019).

The major challenge for farmers is to adapt their soil management to changing environmental conditions, including measures to increase SOC. So far, Germany has been able to cover most of its water requirements in agriculture with the water available from precipitation (Rost et al. 2008). However, the dry summers of 2003 and 2018, for example, have shown how susceptible plant growth is to drought, which has a negative impact on yields (Conradt et al. 2023; McNamara et al. 2024). Therefore, increasing (or maintaining) the SOC content was expected to be an important measure to increase water retention beside other important SOC functions, such as fertility, erosion control, or carbon sequestration, to name just a few (Bünemann et al. 2018). In addition, a reduction in net primary production due to drought comes at the expense of carbon input into the soil, which further reduces the SOC (Bolinder et al. 2007).

The total average increase in PAWC was 1 mm in topsoil and 1 mm in subsoil, with SOC increases by 4 and 5 g kg^{-1}, respectively. Using the potential evapotranspiration as a benchmark, our results suggest that plants have about half a day extra without drought stress, assuming they can root into the subsoil. In reality, however, this could be much more, as actual evapotranspiration is usually lower because it is not assuming unlimited water supply (like the potential evapotranspiration) but is based on the real amount of water that is evaporated from the soil and transpired by plants (Tegos et al. 2013).

On the basis of our study, the highest potential to increase PAWC in topsoil was achieved with long-term FYM application, which resulted in a total average increase of 1.6 mm in the topsoil (Table 3). In the subsoil, the highest increase was observed with deep-ploughing, which increased the PAWC by on average 5.9 mm. However, whether an agricultural measure resulted in positive effects on water retention capacities was very site-specific. As described in the previous chapter, soil texture is an important characteristic of the soil, and increases in SOC cannot compensate for the site conditions, namely, the soil texture.

Furthermore, an increase in the SOC of more than 10 g kg^{-1} can only be achieved with great effort, as can be seen in Table 3, where the maximum increase in SOC was approximately 6.8 g kg^{-1} (buried topsoil). Consequently, we should not overestimate the direct benefits of higher SOC content regarding the water availability for the plants, as also concluded by Minasny et al. (2017). Instead, farmers should focus on the overall positive effects of SOC increase and SOC loss mitigation that can be achieved with agricultural management.

5 | Conclusions

We found effects of SOC on water retention capacities via the reduction of bulk densities in topsoil and subsoil. On average, AC increased by 17% in topsoil and by 134% in subsoil. The high subsoil effect was primarily driven by one sandy site where deep-loosening occurred prior to compost incorporation, which likely contributed to this high increase. PAWC rose by 8% in topsoil and by 3% in subsoil. The average increase in SOC was 4.5 g kg^{-1}, and the corresponding increase in PAWC across all 11 sites was 2 mm in the total soil (0–60 cm), which roughly translates to an additional half day without drought stress for plants. HWC increased by 15% in topsoil and by 7% in subsoil.

Our results have important implications for the agricultural management, especially of PAWC. Expectations that additional SOC will contribute to the adaptation of agricultural productivity to rising temperatures need to be lowered, as the amount of additional PAWCs with increased SOC is limited. Nevertheless, the effects are positive, and a higher SOC content has other benefits (e.g., soil fertility and erosion control), which in turn contributes to climate change adaptation (Lal 2011). We also recognized need for more studies that include the subsoil, as in the present study, as little data is available on the effects of SOC on subsoil water retention capacities. Around 40% of the water retention capacity is located below 30 cm depth, and their exploration is needed to adapt agriculture to increasing extreme weather events.

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Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File 1: jpln70004-sup-0001-SuppMat1.pdf;
Supporting File 2: jpln70004-sup-0002-SuppMat2.xlsx.